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Proofs of the Equation $U=(E/\rho)^{\frac{1}{2}}$ for the Velocity of Sound

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THIS paper consists of four sections. Section 1 outlines the proof of the equation $U=(E/\rho)^{\frac{1}{2}}$ that results from the application, at a particular time, to a thin layer of the medium, of a force due to the difference in pressure between two plane and parallel wave fronts forming the nearby surfaces of the layer. This proof uses the familiar equation $F=Ma$ directly.

Section 2 takes up one of the so-called elementary methods of proof. First, a clear and cogent derivation is given, making use of a considerable mass of air between two wave fronts in appreciably different phases. Then many of the published variations are considered, some of which make use of a "contrary wind." Most of these proofs are obscure and some are wrong. The section is concluded by an integration that forms the logical connection between the argument of Sec. 1 and that of Sec. 2.

Section 3 presents an original proof different from those of the other sections. It does not depend upon any formulation of Newton's second law, but is a consideration of work and the conservation of energy. This proof will be found entirely rigorous and even simpler than that of Sec. 1.

Section 4 gives four correct versions of the proof that follows the motion of a surface separating a part of the medium of normal density at rest from a moving part with density greater than normal. Some of the available derivations of this kind are correct but some are unnecessarily complicated and some are quite wrong.

In order to avoid confusion of symbols we shall use throughout the letters u and U for velocities, reserving V for volume; and because d has other common uses we shall write ρ for density.

1. Newton's Method

The subject of this section is the very simple proof of the equation $U=(E/\rho)^{\frac{1}{2}}$ that follows from a single application of the equation $F=Ma$ to a very thin layer of air between two plane wave fronts. Proofs of this kind are given by Wood,[1] by Crandall,[2] by Frank,[3] by Richardson,[4] by Lindsay,[5] and no doubt by others. Since this derivation is so easily accessible it need not be given in full, but in order to show how simple it is, and to compare it with those of the other sections, and because it is essentially the method by which Newton first derived the equation, and in particular in order that we may establish the connection between this proof and that of Sec. 2, it must at least be outlined. If the term elementary

[1] A. B. Wood, *A textbook of sound* (Macmillan, 1930), pp. 49–52.

[2] I. B. Crandall, *Theory of vibrating systems and sound* (Van Nostrand, 1927), pp. 85–88.

[3] N. H. Frank, *Introduction to mechanics and heat* (McGraw-Hill, ed. 2, 1939), pp. 285–286.

[4] E. G. Richardson, *Sound* (Edward Arnold and Co., ed. 3, London, 1940), pp. 2–4.

[5] R. B. Lindsay, *General physics* (Wiley, 1940), p. 391. In this book, however, the argument is somewhat scattered.

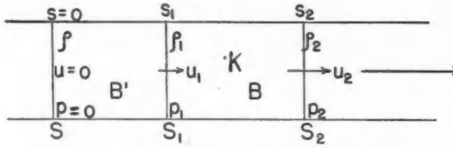

FIG. 1. Plane waves traveling with velocity U in a column of air. Wave fronts S, S_1 and S_2 move toward the right with the constant velocity of the waves. The velocities of the air u, u_1 and u_2, pressures p, p_1 and p_2 (excess above average pressure), and densities ρ, ρ_1 and ρ_2 apply at planes S, S_1 and S_2.

did not somewhat dogmatically exclude the mention of a derivative the following could be rated an elementary proof.

Through Secs. 1 and 2 we suppose that plane progressive waves are maintained in the air in a tube a few feet in diameter by a piston that moves harmonically in the tube. The x-axis is the axis of the tube, the origin is on the axis at the mid-point of the path of the piston, and x is the coordinate of the equilibrium position of any thin layer of air perpendicular to the x-axis. The displacement of such a thin layer parallel to x is y, and at the origin $y=f(t)$, where t denotes time. Then at any x the displacement of the layer, at the same time t, is y_x, and $y_x=f(t-x/U)$. Here U is the velocity with which the disturbance is propagated, without change of type or wave form, along the tube. Then, using partial derivatives, the time rate of change of y, with x at a fixed value (which means the velocity u of a particular moving layer) is $\partial y/\partial t$, and the space rate of change of y, at one value of t, is $\partial y/\partial x$. If we represent $df(A)/dA$ by $f'(A)$, or simply by f', and $d^2f(A)/dA^2$ by f'', whatever the argument A may be, then f' and f'' give the velocity and the acceleration of a layer of air specified by the value of x, at the time t. Similarly $\partial y/\partial x=-f'/U$, and $\partial y/\partial x$ is the strain in the medium, that is $\Delta V/V$. Then $\Delta V/V=-u/U$. Since x is the coordinate of a layer in its neutral or equilibrium position, that is, its position before it was moved at all, dx represents the original length of a short section of the column; hence $\partial y/\partial x$ is the change in volume per unit of original volume. Also $\partial^2y/\partial x^2=f''/U^2$, this being the space rate of change of strain. Now take a layer of air, original thickness Δx, very small compared to the wavelength. Then from one plane face of the layer to the other the strain changes by $\Delta xf''/U^2$. In describing changes in volume of a fluid we note that an increment of pressure ΔP, being positive, produces a decrease in volume. In order to keep the coefficient of elasticity a positive quantity we write $E=-\text{stress/strain}=\Delta P/(-\Delta V/V)$, if ΔV is the change in volume due to ΔP. Hence, for the layer of air under consideration, $\Delta P=-E\Delta xf''/U^2$. Here E is the coefficient of elasticity appropriate to prevailing conditions, in this case γP, where γ is the usual ratio of specific heats. The cross section of the column being A, the mass of the layer is $\rho A\Delta x$. Since Δx is the distance between two layers in their undisturbed (or equilibrium) positions, ρ is exactly the normal density of the air, not an approximation to the density as modified by the wave disturbance. As we pass through this layer in the direction of increasing x the increment of pressure is ΔP, and such an increase of pressure gives rise to a force acting on the layer in the opposite direction, so that $F=-A\Delta P$. This will be recognized as a simple case of the general proposition of hydrodynamics, that force per unit volume is given by the negative of the pressure gradient. Hence the equation $F=Ma$ gives at once

$$AE\Delta xf''/U^2=A\rho\Delta xf'',$$

whence it follows that $U^2=E/\rho$, and $U=(E/\rho)^{\frac{1}{2}}$.

No one could ask for an argument simpler than this. It does require, however, that one know the meaning of a derivative. Of course, anyone who knows the meaning of instantaneous velocity knows also the meaning of a derivative. In addition, the argument requires the basic formula of differential calculus,

$$df(u)/dx=(df(u)/du)(du/dx),$$

where u is some function of x. It requires also the fundamental idea that in the present notation $\partial y/\partial x$ represents strain. But this can be explained in an elementary way.

We now add two names to the list of authors giving proofs of this kind. They are W. F. Magie and Sir Isaac Newton. In his *Principles of physics*[6] Magie gives an argument, without the use of derivatives, but with single letters defined as ap-

[6] W. F. Magie, *Principles of physics* (Century, 1911), pp. 217–219.

propriate rates in their stead, amounting to an application of the equation $F=Ma$ to a thin layer of air. By comparing the acceleration f'' and the quantity h, which is the space rate of change of the space rate of change of the displacement of a layer from its equilibrium position, he shows that the ratio of wavelength to period, or the velocity U, is $(E/\rho)^{\frac{1}{2}}$. The argument with derivatives is easier to follow, because derivatives are symbols that indicate their own meanings. When Magie says he is ". . . following a procedure essentially similar to Newton's" he does more. He illuminates the obscure and difficult argument by which Newton,[7] absolutely without symbols or equations, arrives at his conclusion:

> And therefore the velocity of the pulses will be in a ratio compounded of the square root of the inverse ratio of the density of the medium, and the square root of the direct ratio of the elastic force. *Q. E. D.*

In the proof just given we have distinguished the two pressures of the two sides of the layer and have not distinguished the two accelerations. This is proper, however, because we are concerned with the pressure difference as giving rise to the accelerating force, but we are using the total acceleration, not the variation in it. Hence the average acceleration within the layer is adequate.

After one has struggled with the complicated and fallacious arguments discussed in the next section the simplicity, rigor and brevity of this proof seem almost magical.

2. The Conventional Elementary Proof

The subject of this section is one of the so-called elementary proofs. First will be given a clear rigorous version such as is outlined by Watson.[8] Then some of the different arguments appearing in current textbooks will be examined. Many of them will be found unintelligible or unconvincing.

Figure 1 represents a column of air of cross section A, where plane waves are traveling to the right with velocity U, as in Sec. 1, without damping or change of type. The average pressure in the whole column is P, while p, p_1 and p_2 denote excess pressures above P. Wave fronts S, S_1 and S_2, each in fixed phase, are moving to the right with the constant velocity of the waves; u, u_1 and u_2 are the velocities of the air (taken, like U, with respect to the earth) appropriate to the amplitudes, periods and phases of the vibratory motions at these planes. We have represented S_1 and S_2 within a single condensation that begins at S and extends somewhat beyond S_2. If we take passage within region B or B' and travel with the wave at velocity U we find that at any point fixed with respect to S_1 or S_2 the velocity of the material with respect to the earth does not change. Similarly its acceleration, pressure, density and temperature, all these determined by the existing phase, remain unchanged. We may say that a steady state exists in B and B', and we have only to set forth the consequences of the steadiness. These consequences, when coupled with Newton's second law, lead to the desired conclusion.

Whether we say that material is passing through S, S_1 and S_2, or that these planes, in their motion, pass through material, it is evident that material is being taken into B through S_2 at the rate r_2, where

$$r_2=A\rho_2(U-u_2),$$

and being taken out of B into B' at the rate r_1, where

$$r_1=A\rho_1(U-u_1),$$

and being taken out of B' through S at the rate r, where

$$r=A\rho U.$$

It is a consequence of the steady states in B and B' that these rates are equal. Therefore

$$A\rho U=A\rho_1(U-u_1)=A\rho_2(U-u_2). \qquad (1)$$

Since moving material is entering the region B through S we must agree that momentum toward the right is entering B at the rate R_2, where

$$R_2=A\rho_2(U-u_2)u_2.$$

Similarly momentum to the right is leaving B through S_1 at the rate R_1, where

$$R_1=A\rho_1(U-u_1)u_1.$$

[7] *Sir Isaac Newton's Mathematical principles of natural philosophy and his system of the world.* Translated by Andrew Motte in 1729, revised by Florian Cajori (University of California Press, Berkeley, 1946). Book II, Proposition XLVIII, p. 378.

[8] W. Watson, *A text-book of physics*, revised by Herbert Moss (Longmans, Green and Co., ed. 7, London, 1920), pp. 364–367.

Since

$$A\rho_1(U-u_1)=A\rho_2(U-u_2),$$

and u_2 is greater than u_1, the rates R_2 and R_1 are not equal, R_2 being the greater. Hence momentum to the right is increasing within B at the rate R, where

$$R=R_2-R_1=A\rho_2(U-u_2)u_2-A\rho_1(U-u_1)u_1. \quad (2)$$

We now multiply the second member of Eq. (2) by $A\rho U$ and divide the first term by $A\rho_2(U-u_2)$ and the second term by $A\rho_1(U-u_1)$. This gives

$$R=AU\rho(u_2-u_1). \quad (3)$$

Since $u_2>u_1$, R is positive under the conditions represented in Fig. 1, and Eq. (3) expresses the fact that momentum to the right is increasing within B at the rate R.

However, a continual increase of linear momentum within the fixed volume of region B is incompatible with the existence within B of a steady state. Such an increase is just as intolerable as an increase of mass would be. It is by ignoring this point that certain authors have failed. Something is fantastically wrong with a "steady state" that requires an endless increase of momentum within a region holding a fixed mass with fixed velocities. We cannot impugn the reality of the rate R of Eq. (3). We have shown that the rate exists. However, we can accept the increase, and yet preserve the steady state by the use of Newton's second law.

As indicated in Fig. 1, the excess pressure p_2 at S_2 is greater than the excess pressure p_1 at S_1, and accordingly Ap_2-Ap_1 is a force F acting to the left upon the material within B. This force annuls the increase of momentum to the right given by R. In other words we have in F another rate of change of momentum R' that is opposite to R and must be numerically equal to R. We shall have a total rate of change zero, and we shall save the steady state. We shall also obtain the velocity equation which was to be proved. Accordingly we set

$$A(p_2-p_1)=A\rho U(u_2-u_1).$$

Therefore

$$p_2-p_1=\rho U^2(u_2/U-u_1/U). \quad (4)$$

Since the velocities U, u_1 and u_2 in Fig. 1 are all in the same direction, the medium in B forms part of a condensation, described by

$$u_2/U=-\Delta V/V=-s_2$$

and

$$u_1/U=-\Delta V/V=-s_1,$$

where s_1 and s_2 are the corresponding strains, both negative. That is, in a condensation the characteristic ΔV is a decrease. Hence, by Eq. (4)

$$p_2-p_1=\rho U^2(s_1-s_2). \quad (5)$$

As noted in Sec. 1, E must be a positive constant; therefore, by Eq. (5),

$$E=\Delta P/(-\Delta V/V)=p_2/(-s_2)=p_1/(-s_1)$$
$$=(p_2-p_1)/(s_1-s_2)=\rho U^2. \quad (6)$$

Hence $U=(E/\rho)^{\frac{1}{2}}$, which was to be proved.

It will be noted that the foregoing argument involves no passage of time, no interval, but depends upon instantaneous rates, according to the definition of force as time rate of change of momentum. With this derivation in mind we take up some of the published proofs that follow this general method, first noting two that are correct, then pointing out obvious mistakes in several others.

In Watson's *Physics*[8] the velocity equation is deduced in a clear and exact manner. Letting A and B represent such planes as we have called S_1 and S_2 he says (p. 366),

> Now the momentum contained between A and B must remain constant throughout, for the state of the medium remains the same throughout. There must, therefore, be some cause which produces a loss of momentum exactly equal to the gain we have found above to be produced by the passage of the medium. This cause is the external forces, namely, the pressures at the two planes, which act on the medium contained between A and B.

Watson, accordingly, is consistent in maintaining a really stationary state. He appeals to the pressure difference, not to account for the rate of change of momentum due to material velocities, but to annul it.

The argument given by Capstick[9] is also correct. He says that a certain pressure difference is competent to produce an increase of momentum that will balance the loss due to air leaving a

[9] J. W. Capstick, *Sound* (Cambridge University Press, 1922), pp. 79–81.

limited region with more momentum than the entering air brings in.

Maxwell's *Theory of Heat*[10] gives the development on which many more recent treatments are based. In his account the symbol Q represents the mass per unit area entering or leaving a certain region per unit time through bounding planes A and B, u_1 and u_2 are the velocities of material at these planes, and U is the velocity of the sound waves. After obtaining expressions for momentum transfer at these planes he says:

> Hence the momentum of the entering fluid exceeds that of the issuing fluid by $Q(u_1-u_2)$. The only way in which this momentum can be produced is by the action of the external pressures p_1 and p_2; for the mutual actions of the parts of a substance cannot alter the momentum of the whole.

Here the crucial word is *produced*, for Maxwell shows that momentum to the right is increasing within the region concerned on account of the velocities of material at the bounding surfaces, and then uses the existing pressure difference to *account* for the increase. Thus he leaves the reader to suppose that momentum in this region goes on increasing continually.

Now it may properly be asked, if this is a mistake, actually made, how did Maxwell manage to come out with a correct result. The answer is remarkable. He continues:

> Hence, we find $p_2-p_1=Q(u_1-u_2)$.

Now, in the situation described, p_2 may be greater than p_1, or less, but if $p_2>p_1$ then $u_2>u_1$, and if $p_2<p_1$ then $u_2<u_1$. Hence in the equation quoted from Maxwell we have a positive number set equal to a negative number. He then refers to previous equations, $u_1=U-Qv_1$ and $u_2=U-Qv_2$, where v_1 and v_2 are specific volumes, and says that, therefore,

$$p_2-p_1=Q^2(v_1-v_2).$$

This equation is correct, but it follows from those just quoted only by an obvious mistake in signs. He should have set $p_2-p_1=Q(u_2-u_1)$, above, and then the correct equation would have followed. It is a graceless and hazardous task to find fault with Maxwell. Nevertheless, he leaves his reader, who never suspects that Maxwell can be wrong about anything, in the bewildered contemplation of an endless and infinite increase of momentum between two planes, each in fixed phase. In the seventh edition of the *Theory of Heat*, of 1883, there is a change of sign from the foregoing, but pressure difference is still used to account for the change in momentum due to the motion of substance.

Maxwell attributes the plan of this elementary proof to Rankine.[11] The Rankine paper is hard to read, because the author, using two wave-front planes, says:

> Let the values . . . of the velocity of longitudinal disturbance be u_1 and u_2.

He thus seems to have two different velocities for his sound waves. He also speaks later of "the acceleration" of a body of material that has at any one time many different accelerations. He continues

> Then in each unit of time the difference in pressure, p_2-p_1, impresses on the mass m the acceleration $u_2-u_1\cdots$.

It turns out, however, that Rankine's u_1 and u_2 really mean, and are used as, velocities of material. Then if all his different pressures, velocities and specific volumes are written into a diagram like Fig. 1, it appears that the passage of material results in a decrease of momentum-toward-the-right between the two wave fronts, and this decrease is annulled by the difference in pressure. Most readers are greatly confused by the use of acceleration in this situation.

A version of the elementary proof is given by Barton,[12] who attributes the idea of the contrary wind to Rayleigh. He speaks of two equal masses of air having different speeds at two places A and A'; but this means that equal masses pass through two phase planes (containing the points A and A') in the same time interval, though the moving air has different speeds at the two planes. He continues:

> The cause of this change is to be sought in the difference of pressures at the two points A and A'. For the

[10] J. C. Maxwell, *Theory of heat* (Longmans, Green and Co., ed. 5, London, 1877), pp. 223–227.

[11] This paper was read Dec. 16, 1869, and Maxwell (Ref. 10) cites it as "*Phil. Trans.* 1869," but it should be *Phil. Trans.*, vol. 160, part 2 (1870), p. 277. Carhart (Ref. 13) gives the reference correctly.

[12] Edwin H. Barton, *A text-book on sound* (Macmillan, London, 1908), pp. 177–179.

> prism of gas between them is urged forward by the pressure felt behind and retarded by that experienced in front. Thus the *increase* of momentum between the ends of the prism is due to the *decrease* of pressure throughout its length.

This is very confusing language, for Barton does not mean the increase of the momentum resident within the prism, nor its rate of increase. He means that as the air goes through the space between his two planes it gathers momentum, thus taking out of the region more momentum than it brings in. In this way the decrease of momentum resident between the phase planes is correctly accounted for, a decrease that is annuled by a pressure difference producing momentum in the same direction. It may be agreed that Barton is correct, though obscure.

Carhart's *Physics*[13] is an old book, but it is the model for many recent ones. Carhart follows Rankine pretty closely, citing his paper and Maxwell's *Heat*, and saying:

> The change of momentum of the mass m transferred in one second from one plane to the other is $m(u_2-u_1)$. But the rate of change of momentum is force, or, in this case difference in pressure.

This is also obscure, since neither the mass m nor "the change of momentum" is transferred from one plane to another in one second. A mass m passes through one plane in one second, and a mass m, consisting of different particles, passes through the other in one second. Again a clear statement of the facts is that, due to the passage of material, the momentum resident in the space between the two phase planes changes, and the effect of the pressure difference is to counterbalance that change.

Rayleigh,[14] as has been noted, makes use of the contrary wind, but he does not give anything that may be classed as an elementary proof.

Only a few recent text books of general physics give derivations of the velocity equation. It was the writer's persistent but discouraging attempt to follow the argument of Hausmann and Slack[15] that compelled him to study the whole field of this proof.

Hausmann and Slack follow Carhart closely. Their discussion shows that in a certain time interval a mass m of gas passes a plane B, each very thin layer of m having, when instantaneously at B, a velocity V, this being the velocity of the contrary wind. When one of these layers is at B all the other layers of m have other velocities, different from V. During the same time interval other layers of gas are passing through another plane C, these layers making up a mass equal to m, but composed of different molecules. Each of these layers, when it is at C, has the velocity $V-v$. Obviously Newton's second law gives us no connection between the velocity of a thin layer at C, the velocity of another layer at B at the same time, and the two pressures at B and C. We cannot attribute the difference between these two velocities to the difference in pressure. However, perhaps we should follow one layer from B to C, which, in this argument, is arbitrarily taken to require the same interval, that is the interval required for the mass m to pass through B. Then we have a single object, continent with respect to molecules and material, that has an average acceleration v/t during this interval. When at B this layer finds itself under pressure P_B, and when at C under pressure P_C. By what principle of physics may one attribute the average acceleration of this mass during an interval (brief or otherwise) to the difference between two pressures that affect it only at the beginning of the interval and at the end? Neither of these pressures, nor their difference, is the accelerating force acting on the thin layer. The truth is, of course, that (P_C-P_B) gives a force acting, at any particular instant, on the particular material of mass m that happens to be between the planes B and C at that instant. At any one instant the different layers of m have infinitely many different accelerations, only one of which, if any, could possibly be given by $A(P_C-P_B)/m$. The application of the equation $F=Ma$ to a considerable body of gas having different layers in different phase, and over an appreciable though short time interval, is impossible without a complicated process of averaging which would amount to a calculation of the average acceleration of the center of mass. If one refers the symbols in

[13] Henry S. Carhart, *Physics for university students*, Revised ed. (Allyn and Bacon, Boston, 1906), part 1, pp. 152, 153.

[14] Rayleigh, *The theory of sound* (Macmillan, London, 1906), vol. II, p. 32.

[15] Erich Hausmann and Edgar P. Slack, *Physics* (Van Nostrand, second ed., 1939), pp. 531, 532. The third edition, 1948, gives the same argument, pp. 560–562.

Hausmann and Slack's discussion to a diagram like that of Fig. 1, which is the touchstone of logic and meaning in this derivation, he finds that between planes B and C momentum to the right is increasing on account of the motion of the medium, and the pressure difference is competent, in magnitude and in direction, to annul the increase. In Hausmann and Slack's argument Newton's second law is incorrectly used and there is no proof.

It would be useless to go over all existing derivations of this general type, especially since each one is unique in language and in symbols, though not in idea, and many are obscure. However a few widely used books may be mentioned briefly.

F. R. Watson, in his *Sound*,[16] using the contrary wind, says truly that a particle in a rarefaction has a greater momentum than a particle in a condensation (the wind velocity and the particle velocity being in the same direction in a rarefaction and opposite in a condensation) but continues:

> . . . and this change in momentum must be due to a force, according to Newton's second law. Now the force acting is the difference in pressure. . . .

Obviously this cannot be taken literally, for one cannot attribute the difference between the momenta of two separate particles to any particular force, and the difference between the two pressures at condensation and rarefaction does not give the force acting on any one particle. This is a misuse of Newton's second law.

The proof given by Weniger[17] does not cloud the issue by use of acceleration. However it frankly attributes the net gain in momentum within a fixed volume to the pressure difference existing between the bounding planes. It thus provides for an endless increase in momentum, and therefore need not be analysed in detail.

We close this section by showing how a simple integration leads to Eq. (5), a result just obtained by an elementary method. The essential step is indeed no more than forming the integral of dp from S_1 to S_2 along a line of flow, the integral being taken instantaneously and with respect to distance.

In Sec. 1 we represented the displacement of any layer, from its equilibrium position specified by x, as y_x in the equation $y_x=f(t-x/U)$. The velocity of any infinitely thin layer depends also upon x and t, so that, if Δu is a small change in velocity,

$$\Delta u=(\partial u/\partial x)\Delta x+(\partial u/\partial t)\Delta t.$$

If $\Delta u=0$, then $\Delta x/\Delta t$ must give the velocity of the waves, for to remain at a place where u does not change is to travel with the velocity U. Hence

$$\Delta x/\Delta t=U=-(\partial u/\partial t)/(\partial u/\partial x),$$

or

$$\partial u/\partial t=-U\partial u/\partial x. \tag{7}$$

While the waves are traveling toward the right, as in Fig. 1, let us consider a layer of air of small thickness Δx, and deal with area A of that and neighboring layers. Passing through this layer to the right, Δx is positive and Δp is an increase. This means that a force is acting on the layer toward the left, so that $F=-A\Delta p$. We note that the material at point K in Fig. 1, for example, has its velocity u toward the right, but that, at K, u is becoming less with the passage of time, so that the acceleration of the layer is toward the left, as is required by a force in that direction. Hence

$$F=-A\Delta p=A\rho\Delta x(\partial u/\partial t).$$

Therefore,

$$\Delta p=\rho\Delta xU(\partial u/\partial x).$$

Here we are concerned with differences existing at one time. Therefore, over a thin layer, or in the limit,

$$dp=\rho Udu.$$

We now form the integral from S_1 and S_2 along a horizontal line in Fig. 1, and obtain

$$\int_{S_1}^{S_2}dp=\int_{S_1}^{S_2}\rho Udu,$$

giving

$$\begin{aligned}p_2-p_1&=\rho U(u_2-u_1)\\&=\rho U^2(u_2/U-u_1/U)=\rho U^2(s_1-s_2),\end{aligned}$$

a result identical with Eq. (5).

[16] F. R. Watson, *Sound* (Wiley, 1935), p. 163.
[17] W. Weniger, *Fundamentals of college physics* (American Book Co., 1940), pp. 375–377.

3. A New Proof

In this section will be offered a proof of the velocity equation quite different from anything referred to in Secs. 1 and 2, or published elsewhere, so far as I know. The basic fact is that in plane progressive sound waves the potential and kinetic energies per unit volume are everywhere equal at all times. I have given part of the argument before,[18] but with this fact used as an assumption, justified only by its consequences. Therefore the derivation appeared fallacious to those who could not grant the equality. Here the equality of energies will be proved.

Consider first the work done in giving the piston vibratory motion as in Secs. 1 and 2. The normal pressure in the undisturbed air is P, and behind the piston the pressure is kept constant at the value P. Whether it is difficult to do this, or easy, has no bearing on the argument. The motion of any layer of air is taken, as in Sec. 1, to be an exact copy of the motion of the piston. The displacement of any layer from its position of equilibrium being y, and y being, like the velocity u, a function of x and t, we can write at once an equation analogous to Eq. (7), that is,

$$\partial y/\partial t = -U(\partial y/\partial x). \tag{8}$$

This is, in fact, equivalent to the equation $\Delta V/V = -u/U$ given in Sec. 1. Therefore, whatever agent may be operating the piston is doing work as it advances, for it advances against a condensation, that is, against air at pressure greater than P. The agent does work also, and at the same rate, as the piston recedes, for then it moves against air at constant pressure P and is followed by air at pressure less than P. The piston is, therefore, working, while advancing, at the rate ΔPAu, these symbols having the familiar meanings. While the piston recedes ΔP and u are negative.

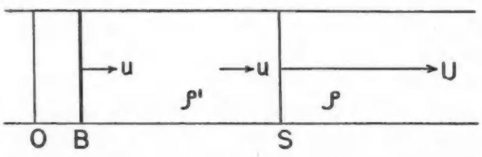

FIG. 2. Motion of a column of condensed air in front of a piston B which moves in a tube at constant velocity u. Plane S separates motionless air of density ρ from condensed air of density ρ' and has velocity U.

There is no mechanism at hand by which energy can be piled up or stored, even momentarily, in a fixed position in the elastic medium. Thus the work done by the piston, appearing as mechanical energy, is transformed and carried off as fast as it is done. Since every state of the air by virtue of which it possesses energy moves along the column with constant velocity U, the energy delivered by the piston is spread along the column, spread thickly if power is great and U is small, thinly if power is small and U is great. If a wide belt is moving north at 10 ft $\sec^{-1}$ and sand is being poured onto the belt from a fixed pipe at 20 lb $\sec^{-1}$, then sand will be distributed along the belt at 20/10 or 2 lb ft^{-1}. Accordingly, the wave train originating at the surface of the piston is being supplied there with energy at the rate ΔPAu, and this energy is being distributed along the column at the space rate $\Delta PAu/U$. Once allotted to the traveling waves, energy is not displaced along the train. Since ΔP and u are together in phase, the energy per unit volume varies along the train between a maximum and zero. Evidently $\Delta PAu/U$ is everywhere a positive quantity, except where it is zero, and e_1, the energy per unit volume, is $\Delta Pu/U$.

Although the air transmitting the waves does not follow Hooke's law, yet for small strains the potential energy per unit volume is $\frac{1}{2}$ stress $\times$strain, or better, since it is convenient to regard energy density as positive, $\frac{1}{2}$ (stress) $\times$(minus the strain due to that stress). Now e_1, being $\Delta Pu/U$, is just (stress)$\times$(minus strain); therefore e_1 is just twice the potential energy per unit volume. The difference, therefore, between the energy e, and the potential energy per unit volume (which is the kinetic energy) must necessarily be $e_{1/2}$, and this is also given by $\frac{1}{2}\rho u$.[2] Therefore $\frac{1}{2}\rho u^2 = \frac{1}{2}\Delta Pu/U = \frac{1}{2}Eu^2/U^2$, since $E = \Delta P/(u/U)$; and $U = (E/\rho)^{\frac{1}{2}}$.

This proof is well within the scope of a general physics course. Anyone who does not agree that the two kinds of energy are equal at every point along the wave train at any time must explain how the energy delivered by the piston is partitioned, and how one part at least is displaced along the train, so that the distribution of po-

[18] W. W. Sleator, "The propagation of energy by waves and the amplitude of a light wave." *J. Opt. Soc. Am.* **21**, 187–204 (1931).

tential energy is different from that of kinetic energy. Many statements can be found to the effect that the distribution is not uniform. Such statements are made, for example, by Crandall (Ref. 2, p. 90) and by Capstick (Ref. 9, p. 68). The latter says:

> The energy is not distributed uniformly over the wave, for we saw that at the points of no velocity there is also no compression, and consequently at these points the air has no energy above what it would have if no waves were passing.

However, the distribution of energy maintained by Crandall and Capstick, in many other books, and in this paper, is definitely opposed by F. R. Watson, who says (Ref. 16, p. 169):

> Halfway between a compression and a rarefaction, the particles have no velocity, and therefore no kinetic energy; but they are displaced the maximum amount from their position of equilibrium, and therefore have potential energy.

Watson does not recognize $\frac{1}{2}$ (stress)$\times$(strain) as potential energy per unit volume, and asserts that the total energy is uniformly distributed along the wave train.

4. Four Correct Versions

In this section we suppose that the piston used to produce the harmonic waves heretofore observed is simply moved forward with constant velocity u. It now carries before it a lengthening column of condensed air terminating at its front in a surface S that advances with constant velocity U. The plane S separates the motionless medium of normal density ρ in front of it from the material of increased density ρ', all of which is moving with velocity u, in its rear. The moving condensed column will increase in mass at the rate r, where $r=\rho AU$. Meanwhile the momentum of the column will increase at the rate R, where $R=\rho AUu$. These circumstances are indicated in Fig. 2, where the surface S and the front face of the piston B started originally at O. Here $OB=ut$ and $OS=Ut$.

Although this situation is universally assumed, it may seem a little arbitrary to state without qualification that the uniformly moving piston carries before it a column of compressed air of uniform density, all at velocity u. Obviously the same velocity throughout implies uniform density, but perhaps neither velocity nor density is everywhere the same. We offer argument and experiment in support of the assumption.

Consider the familiar vertical steel tape firmly supported at one end, with identical horizontal bars rigidly clamped to the tape at equal spaces. The bars are all at rest, and the lower end is free. Grasp the lowest bar and suddenly begin to rotate it about the vertical tape as axis, with constant angular velocity ω. A torsional impulse will move uniformly up the row, and after it has passed the nth bar, that bar is seen to be rotating also with angular velocity ω. The whole lower section is in uniform rotation, and turning as if it were all one rigid body. Each bar is behind the one next below, lagging by the same angle, as far as one can tell by sharp observation. Corresponding behavior is what we ask of the air column ahead of the uniformly moving piston. It did not seem unreasonable in Sec. 1 to expect every layer of air to follow the vibratory motion of the piston. We are now making the same demand while the motion to be followed is simpler. If we should modify the motion of the vibrating piston a little, so that its velocity was constant for $\frac{1}{10}$ of a period near the mid-point of its path, we could expect the compressional waves to show a region of uniform density in the middle of each condensation and each rarefaction. With the piston having uniform motion only, such a region makes up the whole moving part of the column.

We encounter a most interesting situation when we come to complete the proof of the velocity equation by use of the uniform moving column, because no fewer than four different arguments lead to the expression $(E/\rho)^{\frac{1}{2}}$. We take up in order, (1) the use of Newton's second law, (2) the equality of work and energy, (3) the equality of kinetic energy of motion and potential energy of strain, and (4) the application of the equation $F=Ma$.

(1) This proof is already nearly complete. Calling P the normal pressure in the undisturbed air and P' the pressure anywhere in the uniformly condensed column, $A(P'-P)$ is the force pushing the column along, and if there is no friction this force is necessary only because the momentum of the moving column is increasing. It is clear that the change of momentum is taking place only at the surface of separation, and the rate of change

of momentum of the forward quarter of the column, for example, is the same as the rate of change of momentum of the whole. Hence P' may be taken anywhere in the denser part, but we must take P and P' at points a little separated to allow for the acceleration of the very small mass momentarily being added to the moving body. Accordingly,

$$A(P'-P)=\rho A\,Uu=\rho A\,U^2(u/U).$$

Since $u/U=-s$, where s is the strain due to the pressure difference $(P'-P)$, we have at once $E=\rho U^2$, and as before $U=(E/\rho)^{\frac{1}{2}}$.

In his clear and beautiful *Introduction to physics*, R. W. Pohl[19] uses the term *Impuls* as we have used time rate of change of momentum, and gives a concise proof in the foregoing manner. Numerous other authors give this argument with variations. Among them are Grimsehl[20] and Catchpool;[21] the latter notes the effect of an increase of pressure, then of a decrease, uses the second law of motion, and applies the same technique to finding the velocity of transverse waves in a rope. In his derivation Perkins[22] also follows a surface of separation. However, he takes no account of the velocity u of the moving material. Without any use of this velocity it is obviously impossible to calculate or to express the rate of change of momentum of the moving material. Hence the argument fails.

(2) The velocity equation follows also from the equality of work done and resulting kinetic and potential energy. Suppose that to begin with the forces on opposite sides of the piston are equal, and that the force acting on the back surface does not change. The driving agent that moves the piston uniformly along has to exert the extra constant force $A\Delta P$, and when the piston has moved the distance ut, as represented in Fig. 2, that agent has done an amount of work W, where $W=A\Delta Put$. This work is represented by the energy of molecular motion, and the potential energy of distortion, of the condensed part of the column. Referring to Fig. 2, it is obvious that the kinetic energy is $\frac{1}{2}A\,Ut\rho u^2$. The potential energy, being the work required to produce the compression in the moving column, is $\frac{1}{2}\Delta P\Delta V$, or $\frac{1}{2}\Delta PAut$. Therefore,

$$A\Delta Put=\tfrac{1}{2}A\Delta Put+\tfrac{1}{2}A\,Ut\rho u^2, \tag{8}$$

which reduces to

$$\Delta P=\rho Uu=\rho U^2(u/U). \tag{9}$$

Since u/U is $-\Delta V/V$, we have $E=\rho U^2$, or $U=(E/\rho)^{\frac{1}{2}}$, which was to be proved.

Our purpose being to derive the velocity equation, no advantage in simplicity is offered by the work principle. However, this principle is used in their derivation by Millikan, Roller, and Watson.[23] They allow the agent that moves the piston to exert the entire force $A(P+\Delta P)$ instead of our $A\Delta P$, and hence they add the term $P\Delta V$ to each member of an equation equivalent to our Eq. (8), which term is at once subtracted in solving. They do not specifically use the relation $u/U=-\Delta V/V$, but their symbol dV means the change in volume per unit volume, and when they say "The average speed of the piston is $v(-dV)$, where v is the speed of the pulse" (our U) they are saying what is expressed in our terms by $u=-U(\Delta V/V)$. The division of the column into unit cubes has the disadvantage of making their expression for strain $(-dV)$ look like a change in volume, and the velocity of the material and the piston appear as $v(-dV)$ instead of u. The long equation just above their Eq. (281), and our Eq. (8) express the equality of work and energy, and the reduction of either of these to an equation expressing Newton's second law is accomplished by discarding terms that are mostly superfluous if one applies the second law to begin with.

(3) The two terms in the second member of Eq. (8) represent the potential energy of distortion and the kinetic energy of molecular motion separately. Equating these terms gives us $\frac{1}{2}A\Delta Put=\frac{1}{2}A\,Ut\rho u^2$, or $\Delta P=\rho Uu$; therefore $\Delta P=\rho U^2(u/U)$, so that $E=\rho U^2$, a familiar ex-

[19] R. W. Pohl, *Einführung in die Physik, Erster Band, Mechanik und Akustik* (Julius Springer, Berlin, 1930), pp. 187–189. This book is a treasury of excellent lecture demonstrations.

[20] E. Grimsehl, *A textbook of physics*, Seventh German ed., tr. by L. A. Woodward (Blackie and Son. Ltd., London, 1932), vol. 1, *Mechanics*, pp. 217–220.

[21] E. Catchpool, *A text-book of sound*, vol. 1 of the *Tutorial physics* (University Correspondence College Press, London, 1894; Hinds and Noble, New York), Appendix *D*, p. 197.

[22] H. A. Perkins, *College physics* (Prentice-Hall, 1943), pp. 287–288. Also third ed., 1948, pp. 276–277.

[23] R. A. Millikan, D. Roller, and E. C. Watson, *Mechanics, molecular physics, heat and sound* (Ginn, 1937), pp. 362–365. The same argument and the same equation expressing the work principle are given by Millikan and Mills in their *Electricity, sound and light* (Ginn, 1908), pp. 187–190.

pression. The reason for the equality of the two kinds of energy given in connection with the harmonic waves of Sec. 3 is sufficient here. The piston, in fact, is doing work at such a rate that the total energy per unit volume distributed along the wave train is just double the potential energy per unit volume.

(4) The application of the equation $F=Ma$ to the motion taking place in our column of air is not obvious at once, because the moving material has a single constant velocity. However this equation may indeed be used, and in a beautiful, instructive and effective way.

In their elementary proofs of the velocity equation for several types of waves, both Millman and Zemansky[24] and Sears and Zemansky[25] employ the general method of this section and arrange to use Ma for force. They follow the surface separating the material not yet disturbed from the condensed, moving portion, and their equation $s=x/2$ shows that they regard this portion as of uniform density, and as having throughout the same constant velocity. This is u in our terms, and the velocity of the separating surface is U. In effect, they mark off a fixed length to which they give no symbol, but which we will call L. This length L of the original undisturbed column contains the mass ρAL, and they consider the motion of the center of mass of the unchanging mass of air within L, as the condensed portion increases in length, until it includes all the air originally within the length L. They assume that the center of mass of all the air originally within L (not simply the condensed and moving air) has uniformly accelerated motion, and they calculate the acceleration of the centroid on this assumption. However, if they had cared to write out the expression for x_c, the coordinate of the center of mass of the constant amount of material so specified (of which part is in motion with velocity u and part is at rest) they would have found that, at any time t,

$$x_c=L/2+Uut^2/(2L).$$

Since this expression contains a term in t^2 but no higher powers of t, one sees at once that a_c, the acceleration of the centroid c, is constant. Differentiating, we have $u_c=dx_c/dt=Uut/L$, and $a_c=d^2x_c/dt^2=Uu/L$. The constant acceleration Uu/L depends upon the value arbitrarily chosen for L, because any very thin layer is set into motion with a very great acceleration, corresponding to the fact that if L is taken as zero the acceleration is infinite. At the time when $Ut=L$ all the air originally within L is in motion. This is the time chosen by these authors for their value of a_c. In our terms $a_c=u/t$ at this time, and if $x=ut$ and $t=x/v$ we have $a_c=x/(x/v)^2$, as they give it.

It seems simpler to use our value Uu/L for a_c, because obviously, if A is the cross section of the column, the total mass marked off is $A\rho L$, and $Ma_c=A\rho L\,Uu/L=A\rho Uu$. This is exactly what we have given for the time rate of change of momentum of the moving material. Since L does not appear in the end result, it makes no difference what length was chosen for L. In general terms, the constant mass times the acceleration of the center of mass equals the time rate of change of momentum of the variable mass with constant velocity. It is evident that this derivation is an example of the general principle of mechanics, that the centroid of a body moves as if it contained the entire mass of the body, and all the acting forces were applied, with their original magnitudes and directions, at the centroid. But the case of a body of gas partly in motion and partly at rest is not commonly cited as an illustration of that principle.

It would be impossible here to outline all the published proofs and pretended proofs of the velocity equation, but three more of special interest may be cited in closing. These depend upon arguments in which the column of material is first divided into equal blocks. Then a compression is formed that extends, at a particular time, throughout exactly one block. Then the single condensation containing uniformly condensed air that originally occupied a block advances along the column, maintaining its volume and density unchanged.

A derivation of this kind is given by Müller-Pouillet.[26] In this argument the relation of time

[24] S. Millman and M. W. Zemansky, "Wave velocities in elementary physics," *Am. J. Physics* **13**, 250 (1945).

[25] F. W. Sears and M. W. Zemansky, *College physics, mechanics, heat and sound* (Addison-Wesley Press, Cambridge, Mass., 1947), pp. 338–340.

[26] Müller-Pouillet's *Lehrbuch der Physik* (Vieweg und Sohn, Braunschweig, 1886), 9th ed., by Pfaundler, vol. 1, pp. 637–639.

and displacement in the original formation of the condensation is not given, but an expression for the work done by the acting force while the condensation is being transferred from one block to another is equated to the kinetic energy of the moving material. However the calculation of the kinetic energy of a body having many different velocities offers difficulties about which the authors say nothing, and no consideration is given to energy of distortion, and the entire argument is difficult and unconvincing. The proof given by Melde in Winkelmann's *Handbuch*[27] is much like that in Müller-Pouillet, and one seems to have no advantage over the other. The same general judgment can be passed upon the proof given by Chwolson.[28] With the column divided as before and with a single condensation occupying at different times successive single blocks, an expression for force is equated to the product of the mass of a thin layer and its acceleration. The proof is at best a complicated variation of that given in Sec. 1. It is more difficult because the value used for the acceleration is secured on the assumption of a uniformly accelerated motion.

The elaborate demonstration given by Poynting and Thomson[29] may be mentioned here, though it cannot be classified according to the scheme of this paper. It depends upon the equality of force and mass×acceleration, showing the conditions necessary for the propogation of the wave train without change of type; but it can hardly be called an elementary treatment. These authors are followed closely by Duncan and Starling[30] in an argument that could be understood by very few students in a general course.

I wish to acknowledge the benefit of discussions of parts of this paper with David B. Sleator and W. W. Sleator, Jr.

[27] A. Winkelmann, *Handbuch der Physik* (Eduard Trewendt, Breslau, 1891), vol. 1, pp. 792–794.

[28] O. D. Chwolson, *Lehrbuch der Physik*, German ed., tr. by H. Pflaum (Vieweg und Sohn, Braunschweig, 1904), vol. II, *Akustik*, pp. 4–8.

[29] J. H. Poynting and J. J. Thomson, *A text-book of physics*, vol. 2, *Sound* (Charles Griffin and Company, ed. 3, London, 1904), pp. 16–19.

[30] J. Duncan and S. G. Starling, *A text book of physics* (Macmillan, 1925), pp. 690–691.

Certification of Radiation Physicists

Beginning January 1, 1949, The American Board of Radiology will examine and certify physicists as radiation physicists. Three types of certificates will be granted: (1) Radiological Physics; (2) X-ray and Radium Physics; (3) Medical Nuclear Physics.

Each applicant for any one of the certificates in radiation physics will be required to meet the following standards:

(*a*) Satisfactory moral and ethical standing.

(*b*) That he holds himself to be a specialist in the category of physics designated in his application.

(*c*) That he be a citizen of the United States or Canada. Candidates from other countries must be permanent residents of that country and native citizens thereof.

(*d*) That he holds a degree of Bachelor of Arts or its equivalent and has majored in physical science or engineering.

(*e*) That he be a member of the American Physical Society or similar organization.

(*f*) That after graduation from college he has had at least one year postgraduate experience in radiation physics or in a radiation physics laboratory.

(*g*) Candidates for examination in Radiological Physics in addition to requirements specified in paragraphs (*a*), (*b*), (*c*), (*d*), (*e*), and (*f*) must have had at least one year of experience in association with a Department of Radiology approved by the Board and throughout one of the two years specified must have had experience in medical application of artificial radioactive materials.

(*h*) Candidates for examination in X-ray and Radium Physics in addition to requirements specified in paragraphs (*a*), (*b*), (*c*), (*d*), (*e*), and (*f*) must have had at least one year of experience in association with a Department of Radiology approved by the Board.

(*i*) Candidates for examination in Medical Nuclear Physics in addition to requirements specified in paragraphs (*a*), (*b*), (*c*), (*d*), (*e*), and (*f*) must have had one year of experience in physical procedures relative to medical application of radioactive materials.

(*j*) Applications shall be endorsed by a Diplomate of the American Board of Radiology and a Diplomate in Radiological Physics who have personal knowledge of the experience, training, moral and ethical standing of the applicant and that he is qualified to take an examination.

(*k*) A fee of $25.00 shall accompany the application which will be refunded if the application for examination is not accepted.

(*l*) Applications shall be submitted to the Secretary of The American Board of Radiology. Those approved for examination shall be informed by the Secretary of the Board when and where to appear.

Address all communications to the Secretary of the American Board of Radiology.

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The First Published Calculation of Molecular Speeds

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IN his excellent *Memoir of James Prescott Joule*, Osborne Reynolds writes as follows:[1]

"In the summer of 1848 Joule had completed a very bold and successful attempt to submit the dynamical theory of gases to the test of experiment. . . . He gets over the mathematical difficulties by an assumption which shows his insight into the subject, as it is exactly that to which the mathematical solution of the problem would have led him; and from this assumption he calculates exactly what would be the velocity of the particles of hydrogen, supposed all to move with the same velocity, in order to give the experimentally ascertained pressure at a certain density and temperature of the gas. The result he obtains is, for a temperature of 32° Fahrenheit, a velocity of 6055 feet per second, while the most accurate determination that has yet been made gives it as 6049."

Since this result and the method used in obtaining it is given in more or less modernized form in almost every general physics text and since the memoir communicating the result "establishes Joule's position as the founder of the modern quantitative dynamical theory of gases as well as the quantitative dynamical theory of heat," it seems fitting to celebrate the centennial of this important scientific advance by reprinting in full the original memoir.

This memoir, which was entitled *Some Remarks on Heat and the Constitution of Elastic Fluids*, was read before the Manchester Literary and Philosophical Society on October 3, 1848. It was published in the *Memoirs* of that Society in November of 1851[2] and in the *Philosophical Magazine*[3] for 1857. It has been reprinted in *The Scientific Papers of James Prescott Joule.*[4]

Some Remarks on Heat and the Constitution of Elastic Fluids

J. P. Joule

In a paper, "On the Heat evolved during the Electrolysis of Water," published in the 7th volume of the Memoirs of this Society, I stated that the magneto-electrical machine enabled us to convert mechanical power into heat, and that I had little doubt that, by interposing an electro-magnetic engine in the circuit of a voltaic battery, a diminution of the quantity of heat evolved per equivalent of chemical reaction would be observed, and that this diminution would be proportional to the mechanical power obtained.

The results of experiments in proof of the above proposition were communicated to the British Association for the Advancement of Science in 1843.[a] They showed that whenever a current of electricity was generated by a magneto-electrical machine, the quantity of heat evolved by that current had a constant relation to the power required to turn the machine; and, on the other hand, that whenever an engine was worked by a voltaic battery, the power developed was at the expense of the calorific power of the battery for a given consumption of zinc, the mechanical effect produced having a fixed relation to the heat lost in the voltaic circuit.

The obvious conclusion from these experiments was, that heat and mechanical power were convertible into one another; and it became therefore evident that heat is either the *vis viva* of ponderable particles, or a state of attraction or repulsion capable of generating *vis viva.*

It now became important to ascertain the mechanical equivalent of heat, with as much accuracy as lay in my power to give it. For this purpose the magnetic apparatus was not very well adapted; and therefore I sought in the heat generated by the friction of fluids for the means of obtaining exact results. I found, first, that the expenditure of a certain amount of mechanical power in the agitation of a fluid uniformly produced a certain fixed quantity of heat; and, second, that the quantity of heat evolved in the friction of fluids was entirely uninfluenced by the nature of the liquid employed, for water, oil, and mercury, fluids as diverse from one another as could have been well selected, gave sensibly the same result, *viz.* that the quantity of heat capable of raising the temperature of a lb. of water 1° is equal to the mechanical power developed by a weight of 770 lb in falling through one perpendicular foot.[b]

Believing that the discovery of the equivalent of heat furnished the means of solving several interesting phe-

[1] Osborne Reynolds, *Mem. Proc. Manchester Lit. and Phil. Soc.* (4) 6, 191 (1892).

[a] *Philosophical Magazine*, vol. xxiii, pp. 263, 347, 435.

[2] *Mem. Manchester Lit. and Phil. Soc.* 9, 107 (1851).

[3] Series 4, 14, 211 (1857).

[4] Taylor and Francis, 1884, Vol. 1, pp. 290–297.

[b] The equivalent I have since arrived at is 772 foot-pounds. See *Phil. Trans.* 1850, Part I.—J. P. J., May 1851.

nomena, I commenced, in the spring of 1844, some experiments on the changes of temperature occasioned by the rarefaction and compression of atmospheric air.[c] It had long been known that air, when forcibly compressed, evolves heat, and that, on the contrary, when air is dilated, heat is absorbed. In order to account for these facts, it was assumed that a given weight of air has a smaller capacity for heat when compressed into a small compass than when occupying a larger space. A few experiments served to show the incorrectness of this hypothesis: thus I found that by forcing 2956 cubic inches of air, at the ordinary atmospheric pressure, into the space of $136\frac{1}{2}$ cubic inches, $13^{\circ}.63$ of heat per lb of water were produced; whereas by the reverse process, of allowing the compressed air to expand from a stopcock into the atmosphere, only $4^{\circ}.09$ were absorbed instead of $13^{\circ}.63$, which is the quantity of heat which ought to have been absorbed according to the generally received hypothesis. I found, also, that when strongly compressed air was allowed to escape into a vacuum, no cooling effect took place on the whole, a fact likewise at variance with the received hypothesis. On the contrary, the theory I ventured to advocate[d] was in perfect agreement with the phenomena; for the heat evolved by compressing the air was found to be the equivalent of the mechanical power employed, and, *vice versa*, the heat absorbed in rarefaction was found to be the equivalent of the mechanical power developed, estimated by the weight of the column of atmospheric air displaced. In the case of compressed air expanding into a vacuum, since no mechanical power was produced, no absorption of heat was expected or found. M. Seguin has confirmed the above results in the case of steam.

The above principles lead, indeed, to a more intimate acquaintance with the true theory of the steam-engine; for they enable us to estimate the calorific effect of the friction of the steam in passing through the various valves and pipes, as well as that of the piston in rubbing against the sides of the cylinder; and they also inform us that the steam, while expanding in the cylinder, loses heat in quantity exactly proportional to the mechanical force developed.[e]

The experiments on the changes of temperature produced by the rarefaction and condensation of air gave likewise an insight into the constitution of elastic fluids; for they show that the heat of elastic fluids is the mechanical force possessed by them; and since it is known that the temperature of a gas determines its elastic force, it follows that the elastic force, or pressure, must be the effect of the motion of the constituent particles in any gas. This motion may exist in several ways, and still account for the phenomena presented by elastic fluids. Davy, to whom belongs the signal merit of having made the first experiment absolutely demonstrative of the immateriality of heat, enunciated the beautiful hypothesis of a rotary motion. He says:—"It seems possible to account for all the phenomena of heat, if it be supposed that in solids the particles are in a constant state of vibratory motion, the particles of the hottest bodies moving with the greatest velocity and through the greatest space; that in fluids and elastic fluids, besides the vibratory motion, which must be considered greatest in the last, the particles have a motion round their own axes with different velocities, the particles of elastic fluids moving with the greatest quickness; and that in ethereal substances the particles move round their own axes, and separate from each other, penetrating in right lines through space. Temperature may be conceived to depend upon the velocity of the vibrations; increase of capacity on the motion being performed in greater space; and the diminution of temperature during the conversion of solids into fluids or gases may be explained on the idea of the loss of vibratory motion, in consequence of the revolution of particles round their axes at the moment when the body becomes fluid or aeriform, or from the loss of rapidity of vibration in consequence of the motion of the particles through greater space."[f] I have myself endeavoured to prove that a rotary motion, such as that described by Sir H. Davy, can account for the law of Boyle and Mariotte, and other phenomena presented by elastic fluids,[g] nevertheless, since the hypothesis of Herapath—in which it is assumed that the particles of a gas are constantly flying about in every direction with great velocity, the pressure of the gas being owing to the impact of the particles against any surface presented to them—is somewhat simpler, I shall employ it in the following remarks on the constitution of elastic fluids, premising, however, that the hypothesis of a rotary motion accords equally well with the phenomena.

Let us suppose an envelope of the size and shape of a cubic foot to be filled with hydrogen gas, which, at 60° temperature and 30 inches barometrical pressure, will weigh 36.927 grs. Further, let us suppose the above quantity to be divided into three equal and indefinitely small elastic particles, each weighing 12.309 grs; and, further, that each of these particles vibrates between opposite sides of the cube, and maintains a uniform velocity except at the instant of impact; it is required to find the velocity at which each particle must move so as to produce the atmospherical pressure of 14,831,712 grs on each of the square sides of the cube. In the first place, it is known that if a body moving with the velocity of $32\frac{1}{6}$ feet per second be opposed, during one second, by a pressure equal to its weight, its motion will be stopped, and that, if the pressure be continued one second longer, the particle will acquire the velocity of $32\frac{1}{6}$ feet per second in the contrary direction. At this velocity there will be $32\frac{1}{6}$ collisions of a particle of 12.309 grs against each side of the cubical vessel in every two seconds of time; and the pressure occasioned thereby will be $12.309 \times 32\frac{1}{6} = 395.938$ grs.

[c] *Philosophical Magazine*, vol. xxvi.

[d] I subsequently found that M. Mayer had previously advocated a similar hypothesis, without, however, attempting an experimental demonstration of its accuracy ('*Annalen*' of Wohler and Liebig for 1842).—J. P. J., May 1851.

[e] A complete theory of the motive power of heat has been recently communicated by Professor Thomson to the Royal Society of Edinburgh. In this paper the very important law is established, that the fraction of heat converted into power in any perfect engine is equal to the range of temperature divided by the highest temperature above absolute zero.—J. P. J., May 1851.

[f] '*Elements of Chemical Philosophy*,' p. 95.

[g] Mr. Rankine has given a complete mathematical investigation of the action of vortices, in his paper on the Mechanical Action of Gases and Vapours, *Trans. R. S. Edin.* vol. xx. part 1.—J. P. J., May 1851.

Therefore, since it is manifest that the pressure will be proportional to the square of the velocity of the particles, we shall have for the velocity of the particles requisite to produce the pressure of 14,831,712 grs on each side of the cubical vessel,

$$v=\sqrt{\left(\frac{14{,}831{,}712}{395.938}\right)32\tfrac{1}{6}}=6225 \text{ feet per second.}$$

The above velocity will be found equal to produce the atmospheric pressure, whether the particles strike each other before they arrive at the sides of the cubical vessel, whether they strike the sides obliquely, and, thirdly, into whatever number of particles the 36.927 grs of hydrogen are divided.

If only one-half the weight of hydrogen, or 18.4635 grs, be enclosed in the cubical vessel, and the velocity of the particles be, as before, 6225 feet per second, the pressure will manifestly be only one-half of what it was previously; which shows that the law of Boyle and Mariotte flows naturally from the hypothesis.

The velocity above named is that of hydrogen at the temperature of 60°; but we know that the pressure of an elastic fluid at 60° is to that at 32° as 519 is to 491. Therefore the velocity of the particles at 60° will be to that at 32° as $\sqrt{519}:\sqrt{491}$; which shows that the velocity at the freezing temperature of water is 6055 feet per second.

In the above calculations it is supposed that the particles of hydrogen have no sensible magnitude, otherwise the velocity corresponding to the same pressure would be lessened.

Since the pressure of a gas increases with its temperature in arithmetical progression, and since the pressure is proportional to the square of the velocity of the particles, in other words to their *vis viva*, it follows that the absolute temperature, pressure, and *vis viva* are proportional to one another, and that the zero of temperature is 491° below the freezing-point of water. Further, the absolute heat of the gas, or, in other words, its capacity, will be represented by the whole amount of *vis viva* at a given temperature. The specific heat may therefore be determined in the following simple manner:—

The velocity of the particles of hydrogen at the temperature of 60°, has been stated to be 6225 feet per second, a velocity equivalent to a fall from the perpendicular height of 602,342 feet. The velocity at 61° will be $6225\sqrt{\frac{520}{519}}$ $=6230.93$ feet per second, which is equivalent to a fall of 603,502 feet. The difference between the above falls is 1160 feet, which is therefore the space through which 1 lb of pressure must operate upon each lb of hydrogen, in order to elevate its temperature one degree. But our mechanical equivalent of heat shows that 770 feet is the altitude representing the force required to raise the temperature of water one degree; consequently the specific heat of hydrogen will be $\frac{1160}{778}=1.506$, calling that of water unity.

The specific heats of other gases will be easily deduced from that of hydrogen; for the whole *vis viva* and capacity of equal bulks of the various gases will be equal to one another; and the velocity of the particles will be inversely as the square root of the specific gravity. Hence the specific heat will be inversely proportional to the specific gravity, a law which has been arrived at experimentally by De la Rive and Marcet.

In the following table I have placed the specific heats of various gases, determined in the above manner, in juxtaposition with the experimental results of Delaroche and Berard reduced to constant volume.

	Experimental specific heat	Theoretical specific heat
Hydrogen	2.352	1.506
Oxygen	0.168	0.094
Nitrogen	0.195	0.107
Carbonic acid	0.158	0.068

The experimental results of Delaroche and Berard are invariably higher than those demanded by the hypothesis. But it must be observed that the experiments of Delaroche and Berard, though considered the best that have hitherto been made, differ considerably from those of other philosophers. I believe, however, that the investigation undertaken by M. V. Regnault, for the French Government, will embrace the important subject of the capacity of bodies for heat, and that we may shortly expect a new series of determinations of the specific heat of gases, characterized by all the accuracy for which that distinguished philosopher is so justly famous. Till then, perhaps, it will be better to delay any further modifications of the dynamical theory, by which its deductions may be made to correspond more closely with the results of experiment.[a]

[a] If we assume that the particles of a gas are resisted uniformly until their motion is stopped, and that then their motion is renewed in the opposite direction, by the continued operation of the same cause, as in the projection upwards and subsequent fall of a heavy body, the maximum velocity of the particles will be to the uniform velocity required by the theory assumed in the text as the square root of two is to one, and the comparison of the theoretical with the experimental specific heat will be as follows:

	Experimental specific heat	Theoretical specific heat
Hydrogen	2.352	3.012
Oxygen	0.168	0.188
Nitrogen	0.195	0.214
Carbonic oxide	0.158	0.136

I have just learned that the experiments of Regnault on the specific heat of elastic fluids are on the eve of publication, and doubt not that their accuracy will enable us to arrive at a decisive conclusion as to the correctness of the above hypothesis.—J. P. J., June 1851.

I think we shall have to make a real search for the neutron. I believe I have a scheme which may just work, but I must consult Aston first.—J. Chadwick (Letter to E. Rutherford, Sept. 1924).

The Place of Theory in Scientific Method*

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By way of introduction I should like to express the opinion that the working philosophy of the scientist must be an empiricist philosophy. The raw materials with which the scientist deals are empirical data, derived from physical experiments and observations, and the ultimate aim of his manipulation of these raw materials is the prediction or control of other natural events. Thus his activities fall on a path which leads from experimental events out through the realms of theory and then back to other experimental events.

This primacy of the empirical in science really constitutes a metaphysical assumption, and I think that it should be frankly admitted as such. Thus, we do not believe that methods of pure introspection, of mystic communion, or of sheer intuition can possibly yield new knowledge about physical events. The basis for believing this is chiefly the conspicuous failure of all such methods in the past. Of course, we should be aware that no such conclusion can be certain, that conceivably the future could bring a mystic or a necromancer with genuine ability to gain physical knowledge in this way, and in such a case our basic assumptions would have to be changed.

But having embraced the empiricist's outlook in science, it is plainly necessary to go all the way and recognize the empirical basis of all our knowledge of the physical world—everyday knowledge about trees and rocks and small boys, as well as our professional knowledge of crystals and electrons and de Broglie waves. The tree we have known about all our lives, and we have become so accustomed to associating its separate attributes (its color, its shape, its feel) into the single entity which we call tree that we must force ourselves to pause and deliberate in order to recognize that we do this. It is not self-evident from its purely visual aspect, for instance, what the olfactory aspects of the tree will be—we know each of these from having experienced them, and only from having experienced them. We are accustomed to saying that because of the permanence and reproducibility of a certain set of sensory data which we always experience when in the vicinity of a tree that the tree represents a reality independent of ourselves, that it exists. Such a frequently encountered complex of sensory attributes as a tree we will denote by the technical term *construct*.[1]

In a precisely similar way, it is convenient to lump together another frequently occurring complex of items of experience and call them an electron. So long as this classification of items of experience is convenient the term will be legitimate, and one may, if he likes, say that the electron is real, that it exists. The existence thus implied is qualitatively as sound as the existence assumed for a tree. One may object that we actually see the tree, whereas we never see the electron, we only get sensory perceptions from it by way of a rather complex set of instruments—a cloud chamber, a counter, a cathode-ray tube, or a Millikan oil drop. But, for that matter, we do not see the tree either; we see the light which comes from it. And our minds do not really experience the light, but rather the retinal nerve impulses, and so on. The point is that our knowledge of both tree and electron is indirect, and that of the electron is merely more indirect than that of the tree. The difference in the status of the two constructs might be said to be purely quantitative. A future physics might improve on or eliminate the construct of electron altogether, through the invention of a new construct which more adequately correlates the present day electronic manifestations with others perhaps still unknown, whereas it seems highly unlikely that the construct tree will be supplanted by anything better for everyday affairs. So far as we know this difference exists only because of the greater immediacy of trees to our senses. A sapient microbe or a Maxwell demon might regard the electron as an obviously existent entity, but the occasional organization of electrons into trees might seem to him highly conjectural.

* Presented June 11, 1948, at the Roundtable Discussion on *The Scientific Method* at the Colloquium of College Physicists, State University of Iowa, Iowa City, Iowa.

[1] The author wishes to acknowledge his indebtedness to the very lucid discussion of this and related topics by H. Margenau, *Rev. Mod. Physics*, **13**, 176 (1941).

We are now in a position to examine the role which theory must play in scientific investigation. In addition to gathering data the scientist finds it profitable to subject his data to many mental operations of analysis, classification, organization, and the like. For brevity, I think we can describe all these operations as processes of *correlating* the empirical data. These processes serve to make the results of multifarious experiments more easily remembered, more readily encompassed in contemplation, and more easily dealt with in discourse. They also aid in prediction, that is, in correlating the results of past experiments with future experiments, and this is perhaps their most important function. I believe that this correlation of empirical data is what is essentially involved, and is all that is essentially involved, in the formation of a scientific theory. Thus, we could define a theory as simply *a structure of correlations among observed data.* A theory is useful, of course, in direct proportion to the extent of the phenomena which it correlates; it becomes defective when new experiments to which it should apply fail to agree with it; and it becomes obsolete when a new theory is constructed which correlates more phenomena or correlates the same phenomena more simply than the old one. Clearly, to be useful a theory must be capable of application to new experiments, of a similar type but different from, previous experiments used in establishing the theory. It must be more than a mere catalog of a finite number of already completed observations. Consequently every current theory is continually being retested as new experiments within its province are made. Since the number of different experiments in even one simple field is infinite, it is clear that no theory can ever be regarded as established with absolute certainty.

I have given a very simple account of the nature of scientific theories, but it should be obvious that this does not insure that the theories themselves should be simple. Indeed the process of theory formation in physics is largely in the hands of a special group of people who make this their entire work, and who frequently lead strange lives and speak a strange jargon, unintelligible to their friends. In this account I have conspicuously omitted several features which are often expected of theories, such as giving an understanding of nature, explaining phenomena, or giving an insight into reality. I think that in a profound sense the process of *explanation* can never be more than one of correlation of a new phenomenon with a group of phenomena previously interrelated and already familiar to the observer, and hence the above-stipulated type of theory will do all the explaining that can ever be done in science. As to understanding and insight, here again a sufficiently compact and general correlation is all that understanding can really amount to. A theory may give an improved understanding by being stated in picturesque terms, or by being endowed with the features of a mechanical prototype, as for example, when one interprets a quantum mechanical problem in terms of a Bohr model; but the improvement in understandability arises only because the terms of the theory have been made more like the limited experiences of the scientist, not because the theory has been made a more accurate copy of reality.

From the preceding discussion of the empirical basis of all knowledge, it should now be evident that the only demand which a scientific theory must invariably meet is that it should *correlate observations.* This is the irreducible minimum which, on the basis of the present outlook in science, can be expected. Now it should also be mentioned that this is not the maximum which usually has been demanded of theories, and much discussion can be given of additional requirements which are commonly set. At present, all physical theories are made up of two ingredients: *physical constructs*, or concepts, such as trees, electrons, length, energy, and *physical laws.* The constructs are related, by their definitions, to certain clearly delineated elements of physical experience, and the physical laws are brief statements of the correlations to be found among the constructs. These ingredients must be mentally manipulated by the scientist, and in doing this he inevitably employs some basic laws of logic. Up to the present, the logic employed in science has always been Aristotelian logic, the logic of "common sense." Conceivably theories could be devised which are to be dealt with in other systems of logic, and possibly the physics of the future will be handled in such a way. Appealing suggestions have occasionally been made that the probability situation, which seems to be at the heart of microscopic phenomena, could much more naturally be treated under a multi-valued

logic, but pioneering attempts to do this have not been compellingly successful.

A first supplementary requirement of a theory, then, is that a definite brand of logic goes with it. A second requirement of successful theories is that of convenience, or *simplicity*. This is, of course, a relative requirement, and means only that, if two theories are available which equally well correlate data, that which is simpler is to be preferred. The requirement is not grounded upon any necessity for nature to be simple; quite possibly it is not, but the scientist is human and life is short.

A third requirement which is commonly placed on theories is that their ranges of applicability should be as wide as possible. By range of applicability I mean two things. First, I mean the range of types of phenomena to which the theory applies, and second, I mean the range of spatio-temporal localities in which these phenomena may occur. Thus, the kinetic theory of matter is supposed to apply to matter composing biological organisms as well as to an inert gas in a cylinder. It is also supposed to apply to matter in remote nebulae as well as on the earth, and to matter at a previous epoch as well as to matter at the present time and in the future. Notice that in this third requirement *universal* applicability is not demanded. Very many useful scientific theories involve only limited constructs, and thus are applicable only to limited classes of phenomena. The gene theory of heredity, for instance, has nothing to say about the behavior of the atomic nucleus, but this is not regarded as one of its defects. On the other hand some theories accord with observations only when their ranges are arbitrarily restricted among those phenomena which are clearly within their scope, and this is always regarded as a serious drawback. Quantum electrodynamics is exhibiting such a failure in an acute form today.

On the score of their phenomenological range, one may then rank theories in degrees of basicness, and frequently it is assumed, or hoped, that one completely fundamental theory will eventually emerge which will include all the others as special cases. As is suggested by the doctrine of integrative levels,[2] this ideal may be completely unattainable. All that may be said with assurance is that the range of a theory is one criterion of its usefulness, and that if two theories are equal in other respects, the one with the greater range will be regarded as superior.

As a fourth consideration, serving as a useful guide in the framing of theories, it is clear that a new theory must always reckon with an immense body of already established theories, and that it must be in substantial agreement with these theories in regions of their simultaneous applicability, or else be prepared to find favorable experimental evidence on the contradicted points. For brevity, let us call this requirement *consonance with already validated theories*. This requirement is actually no more than a corollary of our one basic tenet, that a valid theory must agree with experiment. In practice, however, it is common to represent a vast number of individual experiments by the validated theories themselves, and preliminary comparison between a new theory and an established theory, in the region of their overlap, is often done entirely on the mental level. Thus, although wave mechanics is at great and fundamental variance with Newtonian mechanics, one of the very useful guides in its development was that it should agree, at least very accurately, with Newtonian mechanics in the realm of everyday masses and energies, a realm in which Newtonian mechanics had already had overwhelming experimental confirmation.

In view of these remarks, the spatio-temporal extensibility mentioned as part of the third requirement may be given a new interpretation: The theory of relativity depends upon a kind of homogeneity of space and time, and any phenomenon whose nature depends upon absolute values of its space or time coordinates does not fit into this theory. The requirement of *permanence* which some writers have placed upon theories may thus be viewed as a consequence of the requirement of Lorentz invariance. Any violation of this, while not at all inconceivable, would also have to account for the numerous experimental results which have, directly or indirectly, been summarized by the relativity principle.[3]

Thus we have recognized one and only one basic, invariable requirement of theories, and we

[2] J. Needham, *Time, the refreshing river* (Macmillan, New York, 1943). R. Ablowitz, *Philosophy of science*, **6**, 1 (1939).

[3] This discussion needs modification, of course, before being applied to cosmological theories.

have also recognized that, by its nature, a theory demands a system of logic for its operation. In addition, we have depicted certain guiding considerations, useful in constructing theories and in arbitrating between rival theories, but not of supreme or final weight. These were: *Simplicity*, *range of applicability*, and *consonance with already validated theories*. Finally, we shall note briefly certain relevant features of the constituent elements of theories.

Constructs, the first of the two ingredients which we have recognized in familiar theories, may be subdivided into two classes: Some constructs are physical *quantities*, such as position, momentum, potential energy, and the like. Other constructs are *physical systems*, such as electrons, molecules, light waves, gases, and so on. The physical systems which entered into the science of an earlier era, for evident reasons, were developed to deal with situations which were only moderately elaborate, and only moderately removed from everyday experience. Consequently it is not surprising that they were not very different from the elements of nature immediately available to everyday experience. The bodies and gravitational attractions involved in the motion of the planets around the sun were very like the bodies and attractions involved in the fall of apples to the earth. But as the observations of science embraced new realms, totally different effects were discovered, and totally new physical systems had to be invented for their correlation. Almost inevitably the demands of common sense were violated in this process, for common sense, after all, involves nothing more than the totality of constructs adequate for phenomena in the everyday range, ingrained in the mind and made so familiar as to seem a part of the necessary appurtenances of thought itself. Similarly the pleasant feature of picturability of constructs may have been lost, for what is picturability but resemblance to constructs within that limited range of affairs which happen to be familiar from everyday observation? As a matter of fact very abstruse things, such as four dimensional space, can be pictured fairly satisfactorily if one intently conditions his mind.

A similar generalization has been necessary in the types of *quantities* admitted to theories. Quantities can be defined in terms of the operations needed to measure them, and classical quantities, when measured, always result in numbers. Thus, length can be laid off with a meter stick, and, through the process of counting, it may have a number attached to it. Not many centuries ago it would have been maintained, I believe, that no such quantity could be permitted in science unless its measurement gave rise to real, positive numbers. Since then, negative numbers have been admitted, as, for example, in temperature measurements; complex numbers have also proved convenient, as in dealing with alternating currents and simple harmonic waves, and, finally, very abstruse mathematical quantities such as tensors, spinors, operators, and vectors in Hilbert space, have more recently been employed in theories. If such complications seem necessary in order to get a theory which will correlate real observations, it seems to me that one can find no methodological fault with the situation, other than on the purely personal grounds that one does not enjoy working with these tools, or is not familiar enough with them to have confidence in them. Thus, in classical mechanics, the quantities which play a primary role are positions and momenta of bodies; in quantum mechanics they are state functions and the corresponding operators, and in a profound sense the latter are just as real, and just as unreal, as the former. Both allow calculations to proceed from initial observations on a system, for instance, to predictions of the outcome of subsequent observations, and each, within its realm of validity, seems to work well. The predictions in the classical case, of course, are of precise values for certain quantities, in quantum mechanics they are of a probability aggregate, so that for an adequate test of the theory many repeated measurements, rather than one, are needed. However, there is no *a priori* reason for thinking the data of experience will not occur in just this way.

In summary, then, we may say that scientific theory should stand as a convenient bridge between various experiments, ordinarily a bridge between completed experiments of the past and contemplated experiments of the future. The constructs and laws of scientific theory need only satisfy the condition of correctly correlating all such experiences. There is no other way of testing whether the constructs and the laws are true, real, or sensible.

Demonstrating the Phase Contrast Principle

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SIMPLE laboratory equipment, set up as in Fig. 1 for demonstrating Abbé's theory of microscopic vision, can be used for showing how *phase contrast* makes visible the detail of transparent objects. The Abbé theory is essentially this: an illuminated object diffracts light falling on it; an optical system collects the diffracted light and recombines it into an image. The distribution of light at each element of area in the image corresponds in amplitude and phase to the light diffracted by the corresponding element of area on the object if the aperture of the optical system is large enough to collect all the diffracted light and if the optical system is perfect as far as geometrical optics is concerned. If the aperture is not large enough to collect all the diffracted light, the image will correspond to a virtual object whose diffraction pattern is just that collected by the optical system. The difference between the virtual object, that is, the image formed, and the object itself is negligible in most cases of ordinary vision. The differences may be great for details so small as to be near the limit of resolution of the optical system. Usually the differences are most noticeable for objects viewed through a microscope. Consequently, Abbé's concept was long believed to apply only to microscopic vision. Porter[1] devised a demonstration similar to, but not exactly like the one in Fig. 1 to show that the concept applied to ordinary vision too.

In Fig. 1, L is a lens with a focal length of about 10 in. Any short focus lens can be used for E; a 5x microscope eyepiece works well. The object O is a wire screen with about 75 wires per inch; a gasoline strainer from an automobile fuel pump will do. The image of a distant light source P is focused on cardboard screen S by L. If O is inserted, the diffraction images formed will also be focused on S. The pattern on S will be of the form shown in Fig. 2. It may have to be viewed with a magnifying glass to ascertain the details of the structure. The lens E is so placed that with S removed an observer at K sees a sharp image of O. If a small hole is cut in S through which only the central image o, Fig. 2, will pass, the observer will see only a blank field without any detail of the object. If a slit is cut in S to pass the central image o and the spectra a, the observer will see the image of a set of vertical wires, the image of the horizontal wires being absent. A set of vertical wires is just the object that would produce the diffraction pattern which was passed by S. If the slit were vertical and placed to pass spectra b, a set of horizontal wires would be observed.

If a slit is made in S to pass only the central image and spectra c, a set of wires parallel to spectra d will be observed. It will also be observed that the wires are closer together than those in the above cases by the factor $1/\sqrt{2}$. If holes are cut to admit only the central image and spectra a_2, one observes vertical wires separated by half the distance observed when spectra a_1 were also passed. In each case the observed image is just the object that would produce the diffraction pattern passed by S. These last two cases are excellent illustrations of the *falsification* of the image that can occur and indicate that care should be exercised in interpreting microscopic images. These demonstrations and others with different combinations of holes in S are well known.[1]

Fig. 1. Arrangement for demonstrating Abbé's theory and the phase contrast principle. Illumination P comes from a distant point source; the object O is a grating of wire or gelatine; L is a lens; S is a cardboard screen in the focal plane of L; E is a microscope eyepiece placed to render visible to the observer at K the image of O formed by L.

[1] Porter, *Phil. Mag.* **11**, 154 (1906).

The Phase Contrast Principle

Consider an optical system with sufficient aperture to allow the amplitude and phase of light at each element of area on the object to appear in the corresponding element in the image. The amplitude will be less at the image if the image is larger than the object, but the amplitude is reduced by the same factor for each

element of area. If the object absorbs light differently at different points, detail will appear in the corresponding image because the intensity of light there varies from point to point. If the object is transparent, every element will show the same amplitude and any detail will be in the phase of the light at different elements. The eye does not respond to phase differences, but only to differences in intensity; thus the detail will be invisible. Phase contrast is a method of converting such invisible phase differences to visible intensity differences.

Zernike[2] has used the following to explain the phase contrast principle. Let the horizontal arrow in Fig. 3 represent the amplitude and phase of the central image in an optical system. This consists of the average vector amplitude of undiffracted light from the object. It will always be of less magnitude than the amplitude of the incident light which is here represented by the radius of the circle. If the object absorbs light differently from point to point but does not change its phase, then the total light amplitude vector in an element of the image will consist of an arrow with its tail at O and its head somewhere on OB. This vector will be composed of the central image **OA** plus another vector representing the sum of the diffracted light. If there is no phase difference over the surface of the object, this vector will be parallel to **OA** and if its tail is placed at A, its head will lie somewhere on OB.

If the object is transparent, but produces different phases at different elements of its surface, the amplitude of every element will be the same and equal to the radius of the circle, OB. If the representing vector's tail is placed at O, its head will lie somewhere on the circle, say at points C, D, or E, but not necessarily at B. If **OA** again represents the central image, that is, the average vector amplitude of the undiffracted light from all the surface elements, then the diffracted light vector for the element with total vector **OC** will be a vector whose head lies at C when its tail lies at A. The elements with total vectors **OC**, **OD**, **OE** are indistinguishable to the eye because they all show the same amplitude and therefore the same intensity. Small phase differences are indicated in Fig. 3. It is with

[2] Zernike, *Physica* **9**, 974 (1942).

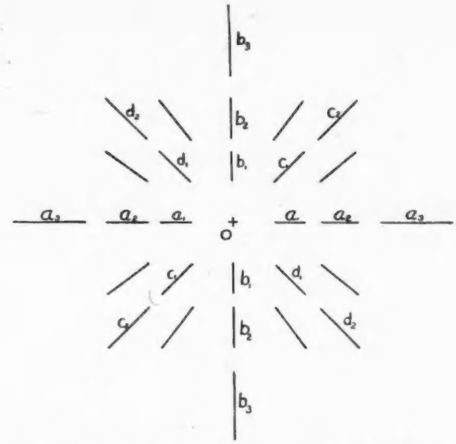

FIG. 2. Diffraction pattern formed by the wire mesh grating or its gelatine replica; a_1, a_2, b_1, etc., are diffraction spectra; o is the white central image; blue falls nearest to o, the color passing through green to red away from o.

small differences that phase contrast is most useful. However, if the central image is cut out, these elements will have light vectors **AC**, **AD**, **AE**, and will show some contrast. This is approximately the situation with dark field illumination. If **OA** has its phase shifted by 90°, either advanced or retarded so that with its head at A, its tail lies at F or G, the light vectors from the elements of the object that were **OC**, **OD**, **OE** will result in vectors **FC**, **FD**, **FE** or **GC**, **GD**, **GE** in the image. A difference of phase at an element of the object produces a difference in amplitude, and therefore intensity, at the corresponding element of the image.

Vectors for an object that shows amplitude contrast and which therefore lie along OB will have more nearly the same amplitude in the image and therefore their contrast will be reduced. In fact, Zernike[3] has shown that a *pure amplitude* grating will be invisible for a central image phase shift of exactly 90°. This is not perfectly realized in practice.

When the phase of the central image is advanced $\pi/2$ or retarded $3\pi/2$, one has *positive phase contrast*, and thicker or more refracting parts of the object appear darker. If the phase of the central image is retarded $\pi/2$ or advanced $3\pi/2$, one has *negative phase contrast*, and the thicker or more refracting parts appear brighter.

[3] Zernike, *Physica* **9**, 686 (1942).

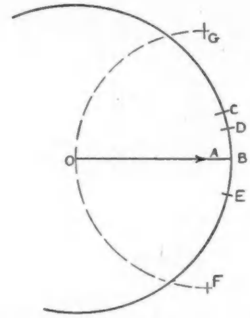

FIG. 3. Diagram of the light vectors at an element of area on the object and the corresponding element in the image.

Zernike[2] discusses reasons for the practice of using a hollow cone of light for illumination in phase microscopy. Under these circumstances an infinity of central images are formed, all lying on a cone where they can be intercepted by an annular phase shifting plate.

Demonstration of the Principle

With the device in Fig. 1 a single point source of illumination consisting of a small filament incandescent bulb at a distance is used, just as with the above demonstrations. The screen wire grating is replaced by a phase grating consisting of a thin gelatine replica of the strainer. The structure of the replica can still be seen from K when S is removed, but the contrast is much less than for the wire. If a horizontal slit is introduced at S, again only vertical lines will be visible. A sliver of mica cemented to S so that it crosses the slit and intersects only the central image will greatly improve the contrast if the sliver has the proper thickness to produce a retardation of an odd number of quarter wavelengths. The mica should be split until it is thin enough to show bright interference colors in white light. Then several samples should be tried until one is obtained that produces the desired improvement in contrast. The difference in contrast is more pronounced if the light is rendered nearly monochromatic by a Wratten No. 58 filter.

The gelatine replica may be made as follows:[4] Dissolve a small amount of potassium dichromate and gelatine in warm water and paint a thin layer of this emulsion on a glass microscope slide. Allow it to dry in the dark or very dim light. Then place the wire screen over the gelatine and make a contact print for ten to thirty minutes a foot from a forty-watt incandescent bulb. Wash the print with warm water for a few seconds and allow to dry. The exposed gelatine will become hardened by the dichromate, while the unexposed gelatine will dissolve, leaving an impression of the strainer. Since the gelatine is transparent, the result is that the thicker parts retard the phase of the transmitted light more than the thinner parts. The difference between ordinary observation and the phase contrast method is greatest when the gelatine is so thin that it is nearly invisible without the phase shifting plate.

Gratings are employed in these demonstrations because their diffraction patterns are simple and widely separated from the central image.

Practical Use of the Principle

The phase contrast principle is of interest in the field of practical microscopy because it allows observations to be made on transparent objects that cannot be stained. Since most living transparent objects cannot be stained without killing the organisms, phase contrast offers a means for observing such organisms alive. Other objects resist staining and hence have been previously unobservable. A great many of these have an index of refraction sufficiently different from their surroundings to be observed by phase contrast. The value of this tool to the biologist is immeasurable.

Bennett[5] has presented a description of some commercially available phase contrast attachments for microscopes and a bibliography on the subject of phase contrast microscopy. He has pointed out that partial absorption of the central image as well as a shift of its phase is desirable for highest contrast with some objects; for others partial absorption of the diffracted image produces higher contrast.

[4] Wood, *Physical Optics* (Macmillan, New York, 1934), 3rd ed., p. 38.

[5] Bennett, *The Scientific Monthly* **63**, 191 (1946).

A Rangefinder Using the Eyes as Objectives

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The optical rangefinder is a device for determining the distance from an observer to some distant object. It usually works on the principle that this distance is a function of the separation of two objectives and the angle subtended by them.[1] Thus, the greater the distance of separation of the objectives, the more accurate the rangefinder will be at greater distances. Although this is a limitation upon the simple rangefinders described in this article, the devices have the advantage of avoiding complicated systems of prisms and lenses. The only lenses used are those in the eye itself.

It is a matter of common experience that an object will produce a double sensation on the brain when the eyes are not focused directly upon it, but rather upon some other object at a different distance. This is due in part to the fact that there exists on the retina of the eye a sensitive portion known as the *fovea centralis*. When looking directly at an object with both eyes, the images formed on the retinas exist at the foveae.[2] At this time the images are apparently in line and the impression of a single object is obtained. The images, of course, are not identical, since they are viewed from different angles, thus giving rise to the stereoscopic effect.[3] If, at the same time that one is viewing a distant object O a second object A falls between the eyes and the distant object, the image of the nearer object appears double for the reason illustrated in Fig. 1 (refraction neglected). The image of A in the left eye, A_L, is to the left of the left fovea, while A_R, the image of A in the right eye, is to the right of the right fovea. Image A_L appears to the eyes to be on the right side of the axis, while A_R appears to be on the left side of the axis. One should remember that the image on the retina of the eye undergoes an inversion in passing through the optic nerve.

Consider next the effect of placing two objects A and B in front of the eye while viewing the distant object O, as shown in Fig. 2(a). There will then be four images produced by A and B on the pair of retinas, and they will appear as shown in Fig. 2(b) when the eyes are focused on the distant object O. Object B is inverted in the figure in order to distinguish it from A. Let us designate these images as follows. Let A_L be the image of A on the left retina, A_R be the image of A on the right retina, B_L be the image of B on the left retina and B_R be the image of B on the right retina.

If A and B are now moved outward from the axis, a point will be reached where A_L and B_R will coincide with O_L and O_R respectively on the foveae and will appear to coincide with each other as shown in Fig. 3. In fact, A and B, if kept the same distance s apart, and the same distance l from the line of the pupils, may be moved together a limited distance to the right or left of the axis and still have A_L and B_R apparently in line with each other as illustrated

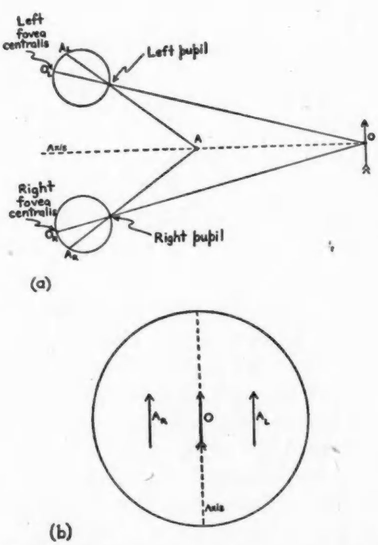

Fig. 1. (a) Production of a double image sensation by a single object. (b) How A would appear to the eyes.

[1] Sears, *Principles of physics III, Optics* (Addison-Wesley, 1946), p. 135.
[2] *Loc. cit.*, p. 111.
[3] Hardy and Perrin, *The principles of optics* (McGraw-Hill, 1932), pp. 517–533.

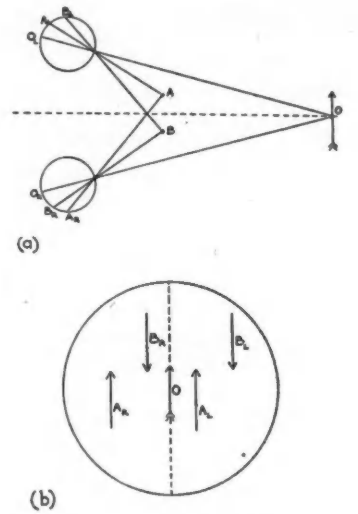

FIG. 2. (a) Geometry of double object producing four images. (b) Appearance to the eyes of A and B when looking at O. Object B is inverted to distinguish it from A.

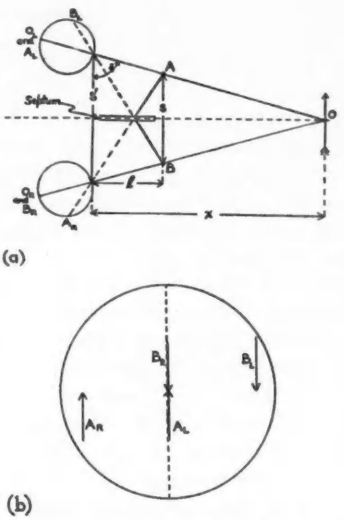

FIG. 3. (a) Geometry of the case when A_L and B_R coincide with the foveae; (b) appearance to the eyes.

in Fig. 3(b). A septum may be introduced to cut out the images of A_R and B_L on the retinas so that they do not confuse the operator in aligning A_L and B_R.

From the geometry of Fig. 3(a)

$$s'/x = s/(x-l)$$

where s' is the interpupillary distance, s is the distance of separation of A and B, l is the distance between the line AB and the line determined by the pupils, and x is the distance of the object O (upon which the eyes are focused) from the line determined by the pupils. The relationship between s and x, the two variables is, therefore,

$$x = s'l/(s'-s). \tag{1}$$

It may thus be seen that a measurement of the range x may be obtained by making a measurement of l, s', and the distance s between A and B when these two points are apparently in line with the object. This relation may also be expressed in angular measure. If φ is the angle between the line of sight of a pupil with the object O and the perpendicular to the axis as shown in Fig. 3, then

$$l/(s'-s) = \tfrac{1}{2}\tan\varphi,$$

and therefore, substituting in Eq. (1), we find

$$x = \tfrac{1}{2}s'\tan\varphi. \tag{2}$$

The change of x with respect to φ is

$$dx/d\varphi = \tfrac{1}{2}s'\sec^2\varphi. \tag{3}$$

The trigonometric function in Eq. (3) approaches infinity very rapidly as the angle φ approaches 90°. This emphasizes the importance of having a large separation s' of the objectives (eyes) if very great accuracy is to be attained at long distances. Fair accuracy can be achieved with this type of rangefinder up to a distance of about 20 feet, which is "infinity" for some types of small cameras.

Equation (2) may be used to calculate the theoretical limit of performance of this type of rangefinder. It is generally accepted that the limiting angle of resolution of the normal human

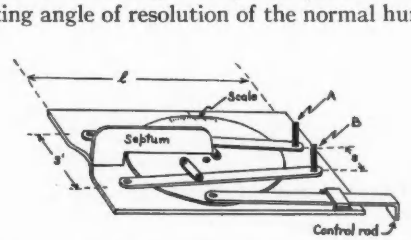

FIG. 4. Model of rangefinder using the eyes as objectives.

eye is about 1 minute. Using a normal interpupillary separation of 62 mm, at an angle φ of 89° 50′ the range is $x=\frac{1}{2}\times 62\times 343.77$ mm $=10.7$ m. This type of rangefinder should ideally, under the above conditions, be able to distinguish between distances of approximately 10 and 11 meters.

Calculation of this deviation may also be made from Eq. (3) letting $d\varphi$ be a small but finite angle of 1 minute. At an angle of 89° 50′ the deviation will be

$$dx=\tfrac{1}{2}\times 62\times \sec^2(89°\,50')\times\frac{2\pi}{360}\times\frac{1}{60}$$
$$=1.06\text{ m.}$$

Thus at an angle φ of 89° 50′, when the range x is about 10.7 m, the deviation will be 1.06 m or about 10 percent of the range. In practice this limit is considerably less.

Figure 4 shows a model of a simple rangefinder employing this principle. The user must hold the rangefinder in the same position relative to the eyes each time and the scale must be calibrated to conform to different interpupillary distances if the instrument is to be used by different individuals. It is quite evident that the degree of accuracy in reading the scale could readily be increased by using a system of levers designed to permit the graduated disk to turn through a greater angle in varying the distance s between A and B.

A second model is illustrated in Fig. 5. Here the same principle is used, but the pointers A and B consist of virtual images formed by reflection of collimated light from two slits, one red, the other green, shining from below upon a slanted piece of transparent glass in such a manner that one image is immediately above the other. Movement of the control rod projecting from the front of the housing results in lateral movement of the lights, and the range is read on the movable scale (calibrated for interpupillary distance) in an opening on the right hand side of the box. A septum, as in Fig. 4, is used so that only one image of each color is seen. The observer simply fixes his vision upon the object whose range is to be determined. He then moves the control rod until the red and green images line up with the object and, more particularly, with each other. The range can then be read on the movable scale on the right. Rotation of the light box about a horizontal pivot is also provided in order to facilitate viewing objects at different distances.

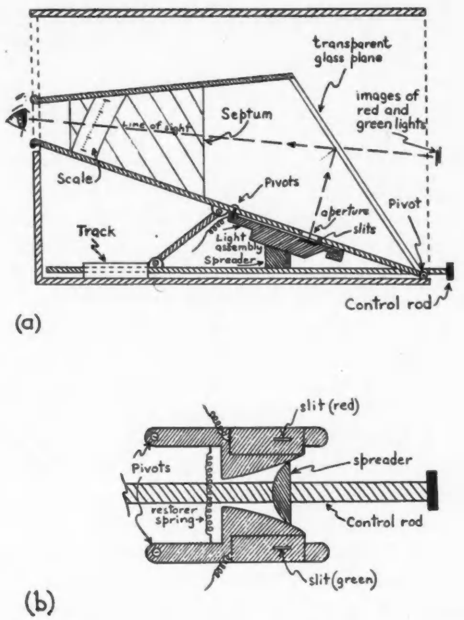

FIG. 5. (a) Model using images of red and green lights as pointers. (b) Detailed top view of light assembly showing action of spreader in moving red and green slits.

This type of rangefinder offers the advantages of simplicity, economy, and ease of construction. It does not pretend to be accurate at distances beyond 20 feet. By properly attaching this instrument to a camera it could be made to focus the camera simultaneously with the process of operation. The model shown in Fig. 5 was designed to fit on a Speed Graphic camera. The operator views the object directly without using the split or double image commonly employed in photographic rangefinders. Some experience and skill are necessary in learning to focus the eyes upon the object instead of the pointers. In fact, the pointers are not in focus on the retinas when a distant object is being observed, but the user can train himself to cut this source of error to a minimum with a little practice. Furthermore, it is conceivable that this instrument could be used for obtaining a quantitative measure of the binocular sense of an individual.

An Apparatus for Measuring the Force Exerted on a Magnet by a Linear Direct Current

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IN the past there has been no simple method for measuring the force exerted by a current on a magnet because of the small magnitude of the force where the current was small and the magnet was of ordinary size and strength. In a previous issue of this journal[1] there was described a two-balance apparatus which permits the simultaneous measurement of the mutual force on the current and the magnet. The apparatus about to be described is a one-balance modification of that with an added feature which makes possible the measurement of the forces for different lengths of current-carrying conductor as well as for different current magnitudes. A laboratory experiment, based on this apparatus, has been in use in the standard course in general physics at Hunter College with results satisfactory to both students and instructors. Its purpose is to enable the students to investigate the force exerted on a magnet by a current in a conductor placed perpendicular to the magnet's field. The relationship between the length of the conductor, the amount of current flowing in the conductor when the magnet's field has the same strength at every point along the conductor, and the force can be observed by the experiment.

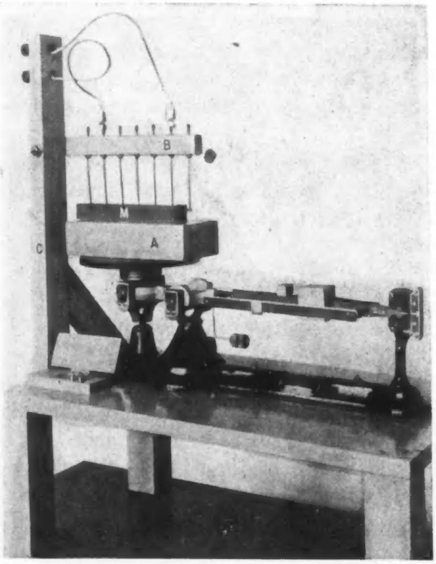

FIG. 1. Photograph of the one-balance apparatus used in measuring the force on the magnet in the field of a linear current.

The Apparatus

A photograph of the apparatus is shown in Fig. 1. The heavy-duty triple beam balance which supports magnet M is fastened to a table with legs 18 cm high, thus placing the balance at a convenient height for securing data. The magnet[2] (Alnico V No. 502-6) weighs about 0.5 kg and is 15.4 cm long, 2.50 cm wide and 2.10 cm high, having an air gap 15.4 cm long, 0.95 cm wide, and 1.00 cm deep between the pole faces. The magnet rests on, without being fastened to, a wooden block A, which is attached to the balance pan with screws.

The wire, which is 15.2 cm long and 2.14 mm in diameter, is suspended in the air gap of the magnet about 10 cm under and parallel to a horizontal cross piece B made of nonconducting material. This is done by using seven vertical No. 16 copper wires, each about 8 cm in length. The lower end of each vertical wire is fastened to the wire in the air gap, and the upper end of each is fastened to B with a brass machine screw so that they divide the air-gap wire into six equal lengths of 2.54 cm each. This makes it possible to have the current flow in different lengths of wire in the air gap. Cross piece B is held in position by bolting one end near the top of a vertical wooden support C, so that the wire will be in the correct position in the air gap. The wire must be between the middle and top of the gap parallel to its long axis and equidistant from each pole face, when the balance is in its equilibrium position.

[1] A. Turner, "Measurement of the mutual forces between a magnet and a wire carrying a direct current," *Am. J. Physics* 16, 310 (1948).

[2] Purchased from Ronald Eyrich, 2566 N. 49th St., Milwaukee, Wis.

TABLE I. Forces on a magnet in the magnetic field of a current.

F (gwt)	Average IL (abamp cm)	F/IL (gwt/abamp cm)
2	1.57	1.27
4	3.11	1.29
6	4.65	1.29
8	6.28	1.27
10	7.83	1.28
		av. 1.28

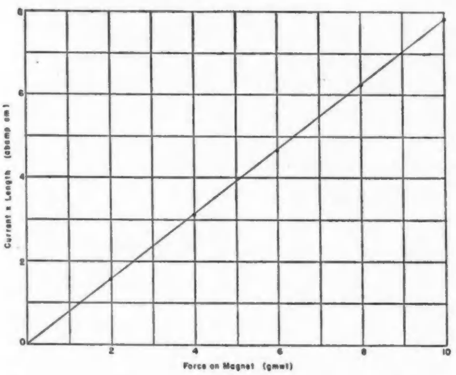

FIG. 2. Graph showing linear relationship between the force acting on the magnet in the field of a linear current and the average product of the magnitude of the current and length of the conductor.

Near the top of C are two binding posts, a wire connected to each. A clip on the other end of each wire can be fastened to any of the machine screws on top of B, so that current may flow into any of the possible lengths of the air-gap wire.

Procedure

The balance is adjusted for equilibrium with no current flowing in the wire. The entire length of the wire should be in the air gap. (Figure 1, shows the wire partly out of the gap merely as a convenience in viewing the wire and the gap.) The clips are arranged so that the current will flow in the desired length of wire in the proper direction to cause the wire and magnet to attract each other. A 2-g weight is then added to the balance pan, and the magnitude of the current is adjusted until the balance is restored to equilibrium. This is repeated for other chosen forces and different lengths of wire.

Results

The data of Table I and the graph of Fig. 2 were obtained by a Hunter College student for forces of attraction. Currents from 1.00 to 10.2 amp in magnitude and from 7.60 to 15.2 cm in length were used. Equally accurate results may be obtained for forces of repulsion. Each average product IL of Table I is obtained from four IL values with four different lengths of conductor in the air gap for a given force. The results of the table and the graph show that the force on the magnet is proportional to the product of the magnitude and length of the current.

I can recall only part of a talk I once heard at a sales meeting. I think the speaker had a point. He said, "You are talking to a parade. Three million Americans never saw an elephant, that is why the circus will come back next year." "Same old stuff" you say—same stunts, same clowns, same animals, same ballyhoo you saw when you were a kid. Yes, largely true, of course, but since that same old elephant stalked through the streets a year ago, three million new Americans will have arrived in this country,—three million more people who have never seen an elephant. That's why the same old elephant walks serenely confident that among every bored group of people who say "That's just an elephant" some eager young voice will shout "Oh! That's an elephant." You are not talking to a grandstand, you are talking to a parade. I think this applies to teaching. The simple experiment that first aroused our interest in physics will have the same effect upon each new group that comes to us for instruction.—R. C. GRUBS. "Demonstrations in High School Physics," *School Science and Mathematics*, XI, 48, 199 (1948).

An Inexpensive Arrangement for Determining e/m by Busch's Method

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University of Colorado, Boulder, Colorado

Not long ago the writers undertook to institute a new e/m experiment for a modern physics course. It was intended to employ an electrostatically deflecting cathode-ray tube with nonmagnetic electrodes especially constructed for this experiment. But the suppliers of this tube could not even promise a delivery date.

An examination of war-surplus cathode-ray tubes sent by the College Gift Department of the Western Electric Company disclosed a tube not unlike one described by F. Wolf.[1] This tube, type 3HP7, is magnetically deflecting and has nonmagnetic elements. It differed markedly from the special one we thought of using for an electrostatic deflection experiment, but turned out to be surprisingly appropriate for the determination of e/m by Busch's method. The internal construction of the tube, socket connections, and circuit diagram are shown in Figs. 1 and 2.

A traveling microscope is focused on the inner and outer surfaces of the glass in the end of the tube. The difference in these readings is multiplied by 1.5, the approximate index of refraction of the glass, to give the thickness of the glass. A cathetometer is used to measure the distance from the outer surface of the glass in the end of the tube to that edge of the ring anode G_2 which is nearer the cathode. This distance, diminished by the thickness of the glass as determined above, is the axial distance L traversed by the electrons.

As indicated in Fig. 3, the cathode-ray tube is mounted inside a solenoid with its axis along the axis of the solenoid and with the midpoint of the distance L at the midpoint of the solenoid. The solenoid is placed with its axis in the magnetic east-west direction to minimize the effects of the earth's magnetic field. The solenoid used here is 76.8 cm in length, 14.1 cm in diameter, and had 689 turns.

The electron beam is focused by increasing the solenoid current until the pip on the screen becomes minimum in size. The voltage of the intensity-control grid G_1 is adjusted for the faintest pip consistent with sharpness of focus. An accurate ammeter is used to measure the solenoid current; readings are taken with the current first in one direction and then reversed, the average value being used in the calculations.

The appropriate expression for e/m under these experimental conditions may be found in nearly

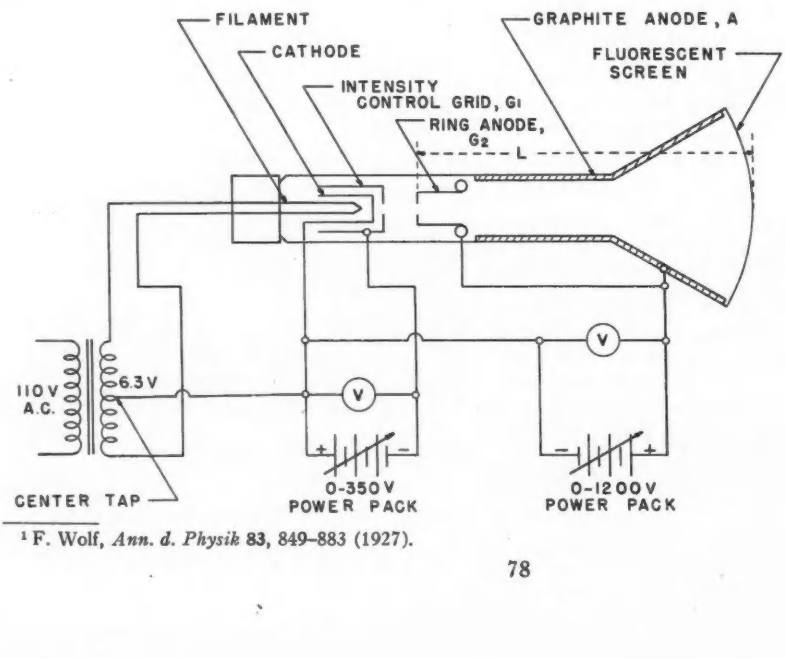

Fig. 1. Internal connections to Western Electric Company, type 3HP7, cathode-ray tube.

[1] F. Wolf, *Ann. d. Physik* **83**, 849–883 (1927).

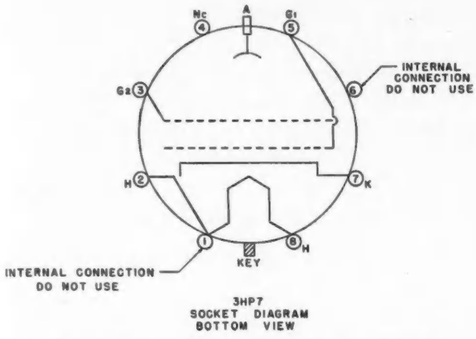

FIG. 2. Socket connections to Western Electric Company, type 3HP7, cathode-ray tube.

TABLE I. Values of e/m for different anode voltages. Axial distance traversed by electrons, $L=18.36$ cm.

Anode voltage (v)	Average solenoid current (amp)	e/m (emu/g)	Percent error
1200	3.62	1.75×10^7	0.6
1109	3.46	1.77	0.6
999	3.33	1.75	0.6
906	3.18	1.71	2.9
806	3.02	1.69	4.0
711	2.84	1.68	4.5
615	2.68	1.63	7.4
517	2.46	1.63	7.4
415	2.26	1.55	11.4
309	1.98	1.50	14.2
139	1.31	1.55	11.4

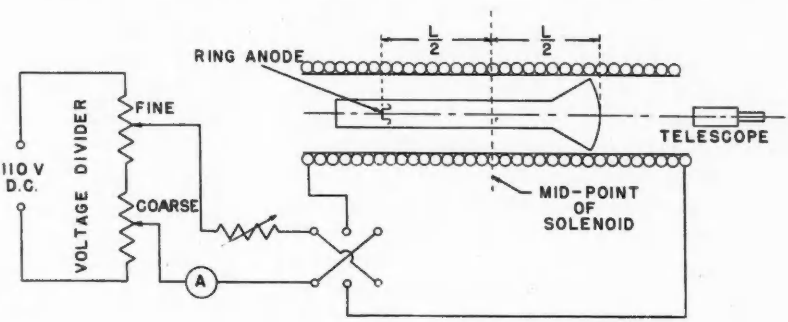

FIG. 3. Location of cathode-ray tube in deflecting solenoid.

any modern-physics textbook.[2] It is

$$\frac{e}{m}=\frac{8\pi^2 V\cos^2\theta}{H^2L^2}.$$

The potential difference V between cathode and anode may be measured with an accurate voltmeter; H, the magnetic field intensity produced by the solenoid, may be calculated from the constants of the solenoid and the average solenoid current. The angle θ at which electrons cross the geometrical axis is small, so that $\cos^2\theta$ may be taken as unity without significant error.

Typical data and results are shown in Table I. It is found that the values of e/m determined by the use of this tube depart from the accepted value at low anode voltages. This may perhaps be attributed to the possibility that the electrons diverge not from the aperture in the ring anode G_2 but from a virtual cathode displaced slightly along the axis of the tube. Experience has indicated that the results obtained by this arrangement make the experiment a valuable one in a laboratory course.

[2] J. D. Stranathan, *The "particles" of modern physics* (Blakiston, 1942), p. 118.

It is the great beauty of our science, that advancement in it, whether in a degree great or small, instead of exhausting the subject of research, opens the doors to further and more abundant knowledge, overflowing with beauty and utility.—M. FARADAY.

Opportunities for Graduate Study in Physics

THE four tables forming the main part of this announcement give a summary of opportunities for graduate study in physics that will be available in September, 1949. For help in gathering the necessary information, the Editor is grateful to the American Institute of Physics for providing addressed envelopes, and to the heads of departments of physics in all parts of the country who took time to answer a questionnaire mailed to them early in October, 1948. All but a few of the graduate schools referred to are in the United States. The figures quoted are correct insofar as they could be estimated a year in advance of the event, but they should be used, and are intended to be used, as a guide only. Prospective applicants are urged to write for full information to the Deans of the Graduate Schools, or to the Heads of the Departments of Physics at the institutions of their choice.

In preparing the questionnaire an attempt was made to distinguish between three common types of opportunity for graduate study: (1) Part-time graduate study and part-time teaching; (2) part-time graduate study and part-time assisting in research; (3) graduate study with tenure of a predoctoral fellowship. The manner of gathering data will be clear from the questionnaire which is reproduced below. There were 22 questions, designated by the letters A, B, C, $\cdots$, by which symbols the answers have also been catalogued in Tables I, II, III, and IV. Following some of the questions are notes in finer print. These were not part of the questionnaire but were added during the preparation of this article to make clear the meanings of the entries in the Tables which follow.

Letters were mailed to 677 departments of physics with the request: "Please complete the questionnaire below, giving data for your own institution. . . . Answers good to 25 percent will be satisfactory for items like *E*, *F*. Stipends should be quoted, if possible, with errors of not more than 10 dollars."

The Questionnaire

A. Name and address of institution.

B. Approximate enrollment, graduate students in physics only.

C. Highest degree offered in physics.

D. Number of teaching and research staff in the department of physics, excluding assistants and predoctoral fellows.

Combination of graduate study and research

E. Number of half-time graduate assistants employed.

F. Number of half-time graduate assistantships probably available in September, 1949.

Sometimes this was interpreted to mean the number of vacancies to be filled; sometimes to mean the total number likely to be employed. A comparison with the answer to the preceding item usually makes the meaning definite.

G. Stipend in dollars for half-time graduate assistant possessing B.S. degree (including any fees that are waived).

In many cases the answers were given *not* including fees that are waived. When the symbol + follows the stipend quoted in the Tables, the meaning is that, in addition, fees are waived. Sometimes there is a range of stipends.

H. Stipend in dollars for half-time graduate assistant possessing M.S. degree (including any fees that are waived).

The note after item *G* is also applicable here.

I. Are some appointments made with a different time distribution between teaching and graduate study; for example $\frac{1}{4}$ teaching, $\frac{3}{4}$ graduate study?

Combination of graduate study and assisting in research

J. Number of half-time research assistants employed; that is, half-time graduate study, half-time assisting in research.

K. Number of half-time research assistantships available in September, 1949.

The note accompanying item *F* is applicable here.

L. Stipend in dollars for half-time research assistant possessing B.S. degree (including any fees that are waived).

See note after item *G*.

TABLE I. Graduate schools enrolling 51 or more students in physics.

Name and Address of Institution	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
Brown University Providence 12, R. I.	51	Ph.D.	11	17	5	900+	1000+	Yes	14	5	900+	1000+	Yes	U	1	1	1.0	0.25	750+ −1000+	M.S.	U
California Inst. of Tech.[1] Pasadena 4, Calif.	80	Ph.D.	30	20	8	750+	750+		10	5	750+	750+	Yes	N	3	2			750+ −1000+		U
California, Univ. of[2] Berkeley, Calif.	222	Ph.D.	28	72	75	1200	1200				See footnote 2			S	11						
California, Univ. of Los Angeles 24, Calif.	100	Ph.D.	18	35	35	1200	1200	Yes	4	4	1200	1200	No	S	1		0.5	0.5	1600	M.S.	U
Carnegie Inst. of Tech. Pittsburgh, Pa.	60	D.Sc.	18	30	12	750 −1000	850 −1150	Yes	20	5	750+ −1000+	1000+ −2100+	Yes	U	12	6	1.0	0.5	1000 −2100	B.S.	U
Catholic Univ. of America[1] Washington 17, D. C.	80	Ph.D.	12	10	3	900+	900+	Yes	8	2	1.50/hr.	1.50/hr.									
Chicago, Univ. of Chicago, Ill.	160	Ph.D.	18	14	14	1500	1500	Yes	15	15	1500	1500	Yes	N	15	10	1.0		1500 −2000		U
Columbia University New York 27, N. Y.	180	Ph.D.	22	30	8	1800	1800	Yes	20	10	180/mo.	200/mo.	Yes	S	5	5	1.0	var	1000 −1700	Ph.D.	
Cornell University Ithaca, N. Y.	90	Ph.D.	24	55	20	1000+ −1200+	1000+ −1200+	No	19	10	1200+ −1400+	1200+ −1400+	No	N	1	1	var	1.0	600		
Harvard Univ. and Radcliffe Coll. Cambridge, 38, Mass.	96	Ph.D.	20	16	16	1500	1500	Yes	7	7	1500	1500	Yes	N	10	10	var	var	525 −1200	A.B.	U
Illinois, Univ. of Urbana, Ill.	130	Ph.D.	29	56	10	1200+	1200+	Yes	23	6	1620+	1620+	Yes	N	9		1.0	1.0	700+ −1000+	B.S.	U
Iowa State College Ames, Iowa	60	Ph.D.	40	16	20	720+	1000+	No	25	25	135/mo.	165/mo.		N	20		1.0	var	900 −1200	B.S.	
Johns Hopkins University Baltimore 18, Md.	60	Ph.D.	19	24	8	1307	1307	Yes	16	5	1500 −1800	1500 −1800	Yes	U	9	3			400 −1500		U
Maryland, Univ. of College Park, Md.	240	Ph.D.	10	16	16	1000+	1000+	No							12	12	0.5	0.5	600	B.S.	
Massachusetts Inst. of Tech. Cambridge 39, Mass.	177	Ph.D.	48	26	9	1100+	1100+	Yes	30	10	1735	1735	Yes	U	6	6		1.0	600 -1800	B.S.	
Michigan, Univ. of Ann Arbor, Mich.	160	Ph.D.	20	26	12	1200	1200	Yes	10		1000 -1500	1200 -1800	Yes	S	8		1.0	0.5	1000 -1500	M.S.	U
Minnesota, Univ. of Minneapolis, Minn.	60	Ph.D.	12	34	32	900+	900+	Yes	8	8	900+	100+/mo.	Yes	N							
New York University Washington Square New York, N. Y.	180	Ph.D.	12		5	600	750	No	8	4	500 -750	750 -1000	Yes	S	2	4	0.75	0.25	2000	B.S.	S
Ohio State University Columbus, Ohio	125	Ph.D.	27	40	10	810+	900+ -1350+	No	10	5	1500+	1800+	Yes	S	2	2	0.5	0.5	1800	M.S.	U
Pennsylvania State College State College, Pa.	69	Ph.D.	25	18	24	1360	1360	Yes	10	16	1360	1360	Yes	U	5	6	0.5	0.5	2000 -3000	M.S.	U
Pennsylvania, Univ. of Philadelphia 4, Pa.	100	Ph.D.	20	20	5	100+/mo.	120+/mo.	Yes	14	5	100+/mo.	120+/mo.	Yes	N	3	3	1.0	1.0	1000 -1500	M.S.	N
Pittsburgh, Univ. of Pittsburgh 13, Pa.	72	Ph.D.	19	20	20	1000+	var	Yes	12	3	100+/mo.	100+/mo.	Yes	U			0.75	0.5		B.S.	U
Purdue University Lafayette, Ind.	85	Ph.D.	21	52	15	1300	1600	Yes	18	5	1300	1600	Yes	U	5	2	0.75	0.5	1500 -2000	M.S.	U
Stanford University Stanford, Calif.	65	Ph.D.	13	18	18	900	900 -1080	Yes	30	30	1050	1250	Yes	U	2	2	0.7	0.5	500 -700	B.S.	U
Tennessee, Univ. of[1] Knoxville, Tenn.	75	Ph.D.	20	10		800+	1000+	Yes							2	2	0.5	0.5	1200	B.S.	U
Texas, Univ. of Austin, Texas	60	Ph.D.	15	40	35	1000	1200	Yes	6	4	900	900	Yes	S							
Washington, Univ. of Seattle, Wash.	65	Ph.D.	18	42		367/qr. -397/qr.	397/qr.	Yes	10		367/qr. -397/qr.	397/qr.	No	S							
Wisconsin, Univ. of Madison 6, Wis.	100	Ph.D.	18	-43	10	1100+	1100+ -1200+	Yes	36	8	900+ -1100+	900+ -1100+	No	U	6	3	0.5	0.5	800 -2400	B.S.	U
Yale University New Haven, Conn.	80	Ph.D.	24	18	18	1300	1300	Yes	25	25	156/mo.	156/mo.	Yes	U	12	12	1.0	0.8	450 -1600	B.S.	U

[1] All graduate assistantships require one-quarter time teaching.
[2] Items *J*, *K*: The Radiation Laboratory of the Atomic Energy Commission employs 55 graduate students for 20+hr./wk., compensation variable. Item *P*: Some of these are fellowships of the Atomic Energy Commission.

TABLE II. Graduate schools enrolling from 26 to 50 students in physics.

Name and Address of Institution	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
Case Institute of Tech. Cleveland, Ohio	40	Ph.D.	11	16	6	1350	1500	Yes	4	2	1350	1500	Yes	U	2	2	1.0	1.0	1500	B.S.	U
Colorado, Univ. of Boulder, Colo.	26	Ph.D.	20	12	6	750	800 -1150	No	3		1.00/hr.		No	N							
Duke University Durham, N. C.	30	Ph.D.	10	8	8	900 -1200	1350 -1500		14	14	80/mo. -110/mo.	150/mo. -200/mo.		U	1	2	0.5	0.5	1500	B.S.	U
Fordham University New York, N. Y.	40	Ph.D.	5	5	2	600	600	Yes	3	2	600	600	Yes	S	3		1.0	0.5		M.S.	U
George Washington Univ. Washington, D. C.	35	Ph.D.	8	2	3	1260	1260	Yes													
Indiana University Bloomington, Ind.	50	Ph.D.	9	23	12	1000 -1500		No	12	6	1200 -1500		No	U	1				1000+		
Iowa, State Univ. of Iowa City, Iowa	40	Ph.D.	9	18	18	900+	900+	Yes	6	6	900+	900+	Yes				1.0	1.0	330 1150−		
Kansas, Univ. of Lawrence, Kansas	35	Ph.D.	11	19	20	900	1000	Yes	3	8	900	1000	Yes	S	4	4			300 -700		
Kentucky, Univ. of Lexington 29, Ky.	28	Ph.D.	15	10	10	90/mo.	90/mo.	No	0	2	100/mo.	100/mo.	No	S	2	2	0.5	0.5	1500 -2000	M.S.	S
Lehigh University Bethelehem, Pa.	26	Ph.D.	15	14	6	1000+	1000+	Yes	4	2	1000+	1000+	Yes	S	1	1	0.5	0.5	750+	B.S.	S
McGill University[1] Montreal 2, Canada	45	Ph.D.	11	10		750	750 -1500	Yes	15		750	750 -1500	Yes	S	4	5	0.75	0.75	100/mo. -250/mo.		S
New York Univ. (Coll. of Eng.) Univ. Hgts., New York 53, N. Y.	30	Ph.D.	14	11	6	1473	1473	Yes	3	1	1200	1200	Yes	S							
North Carolina, Univ. of Chapel Hill, N. C.	34	Ph.D.	9	12	4	1188	1188	No	3		900	1100	Yes	N							
Northwestern University Evanston, Ill.	45	Ph.D.	40	17	8	1500	1500 -1600	Yes	5	4		1600 -2500	Yes	S		1	0.7	0.3	1200 -1800	M.S.	U
Notre Dame, Univ. of Notre Dame, Ind.	38	Ph.D.	14	25	10	1300	1400 -2500	Yes	8		1300	1400 -2000	Yes	S	4		0.75	0.5	2000 -2500	M.S.	U
Oklahoma, Univ. of Norman, Okla.	37	Ph.D.	10	20	9	810	1080	Yes	4	1	810	1080	Yes	U	2	2	0.25	0.75	300 -500	B.S.	U
Princeton University Princeton, N. J.	45	Ph.D.	25	11	12	1100+	1200+	No	7	10	1100+	1200+	No	S	20	20	0.5	0.5	400 -1800	B.A.	U
Rensselaer Polytechnic Inst. Troy, N. Y.	35	Ph.D.	35	6	4	1650	1650	Yes		4	1650	1650	Yes	S	10	10	0.4	1.0	1200	B.S.	S
Rice Institute[2] Houston, Texas	30	Ph.D.	7	15	5	750	800+ -900+	Yes	1	1		800+ -900+		U	5	2	0.5	0.5	850 -1500	M.S.	U
Rochester, Univ. of Rochester, N. Y.	35	Ph.D.	12	30	6	1000+	1000+	No	2	4	1000	1000 -1500	No	U	1	1	0.8		1200 -1600	B.S.	U
Southern California, Univ. of Los Angeles 7, Calif.	50	Ph.D.	15	20	10	1050 -1250	1250	Yes	10	3	1500 -2000	1800 -2400	Yes	U							
Stevens Institute of Tech. Hoboken, N. J.	30	M.S.	12	3	2	120/mo. -175/mo.		Yes													
Syracuse University Syracuse, N. Y.	42	Ph.D.	14	30	10	1250	1250	Yes	4	2	1250	1250	No	N	2	2	0.75	0.25	1100	M.S.	U
Virginia, Univ. of Charlottesville, Va.	33	Ph.D.	5	13	9	500 -600	600 -900	Yes	2	4	115/mo.	150/mo.	Yes	N	5	4	0.75	0.75	750 -1500	M.S.	
Washington University St. Louis 5, Mo.	45	Ph.D.	9	24	24	1250	1500	No	10	10	1250	1500	No	N	5	5	0.75	0.75	800 -1500	M.S.	U

[1] Most graduate assistantships require one-third time teaching.
[2] All graduate assistantships require one-quarter time teaching.

TABLE III. Graduate schools enrolling from 11 to 25 students in physics.

Name and Address of Institution	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Alabama Polytechnic Inst.[1] Auburn, Alabama	15	M.S.	10	1	2	100/mo.	100/mo.	Yes	11	18	150/mo.	250/mo.	Yes	U	1	6
Boston College Chestnut Hill 67, Mass.	11	M.S.	10	6	10	1000		No								
Buffalo, University of Buffalo 14, N. Y.	24	Ph.D.	16	15	10	1000 -1200	1200+	Yes	0	3	1000+	1200+	Yes	S		
Cincinnati, Univ. of Cincinnati, Ohio	20	Ph.D.	10	4											5	5
The College, Univ. of Chicago Chicago, Illinois	15	M.S.	10	0	2	1275		Yes	0	1	1275			S		
Florida, State Univ. of Gainesville, Florida	13	M.S.	11	7	12	900+		No	0	2	900					
Illinois Institute of Tech.[2] Chicago 16, Ill.	25	Ph.D.	12	3	6	1314	1500 -2000	Yes	0	1		3000	Yes	S		
Kansas State College Manhattan, Kansas	14	Ph.D.	18	10	8	1215+	1215+	Yes	2	2	1215+	1215+	Yes	U		
Louisiana State Univ. Baton Rouge, La.	25	Ph.D.	8	13	12	720 -990	720 -990	No	3	3	900		No	N		
Marquette University Milwaukee, Wis.	15	M.S.	5	3	3	90/mo.	110/mo.									
Michigan State College East Lansing, Mich.	13	Ph.D.	18	5	2	1000+	1200+	Yes	0	1	800+	1000+	Yes	U	2	1
Missouri School of Mines Rolla, Mo.	14	M.S.	13	2	4	810		Yes								
Missouri, Univ. of Columbia, Mo.	20	Ph.D.	8	5	3	750 -1000	1400	Yes	2		93/mo.		Yes	S	2	3
New Mexico, Univ. of Albuquerque, N. M.	18	Ph.D.	6	6	6	900	1200	Yes	1	3	800	1200	Yes	S	1	2
Oklahoma A. and M. Stillwater, Okla.	12	M.S.	14	6	6	1000		No	0	2	1000			S		
Oregon State College[1] Corvallis, Oregon	23	Ph.D.	14	2	4	800 -900	1000 -1100	Yes	4	4	800 -900	1000 -1100	Yes	S	1	1
Oregon, Univ. of[1] Eugene, Oregon	11	Ph.D.	6	9	10	725 -845	845 -875	Yes	2	3	965	1085	Yes	S		
Rutgers University New Brunswick, N. J.	25	Ph.D.	15	16	5	1080+	1080+	No							3	0
Temple University Philadelphia 22, Pa.	25	Ph.D.	10	7	2	1100	1200	No								
Texas, A. and M. College of College Station, Texas	12	Ph.D.	18	8	8	100+/mo.	110+/mo.	Yes	0	2	100+/mo.	110+/mo.		S		
Tulane University New Orleans, La.	16	M.S.	11	5	8	800	900	No	7	4	1000	1200	No	S	1	1
Union College Schenectady 8, N. Y.	24	M.S.	6	0	1	1200		Yes								
Utah, Univ. of Salt Lake City 1, Utah	18	Ph.D.	6	13	14	500 -750	750	Yes	2	3	750 -1200	750 -1200	Yes	U		
Vanderbilt University[2] Nashville 4, Tenn.	19	Ph.D.	9	8	10	720	720	Yes							8	
Washington, State College of Pullman, Wash.	12	Ph.D.	8	8	8	900+	900+	Yes	7	7	900+	900+	Yes	N	7	7
West Virginia Univ. Morgantown, W. Va.	11	M.S.	10	5	2	900		Yes								

[1] All graduate assistantships require one-third time teaching.
[2] Most graduate assistantships require one-third time teaching.

TABLE IV. Graduate schools enrolling fewer than 11 students in physics.

Name and Address of Institution	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
Akron, Univ. of Akron, Ohio	5	M.S.	3	1	4	1000 –1200		Yes	
Alabama, Univ. of University, Ala.	7	M.A.	6	4	4	937		Yes	
Amherst College Amherst, Mass.	3	M.A.	5	3	3	1000 –1600	1600 –2000	No	
Arizona, Univ. of Tucson, Arizona	6	M.A.	8	2	2	750+		No	
Arkansas, Univ. of Fayetteville, Ark.	3	M.A.	4	1	2	900+		Yes	0
Bradley University Peoria, Ill.	6	M.S.	4	0	2				
Bryn Mawr College[1] Bryn Mawr, Pa.	6	Ph.D.	3	2	1	1100	1100	No	2
Bucknell Univ. Lewisburg, Pa.	2	M.S.	5	2		1800		No	
Carbon Junior College Price, Utah	2	M.S.	2						
Clemson Agr. College Clemson, S. C.	6	M.S.	13	3	6	1000+ –1200+		No	
Dartmouth College Hanover, N. H.	7	M.A.	9	5	3	1500+		No	2
Delaware, Univ. of Newark, Del.	10	M.S.	10	2	4	1000+		No	0
Detroit, Univ. of Detroit, Mich.	10	M.S.	8	1	6	1150		No	
East Texas State Tchrs. Coll. Commerce, Tex.	3	M.S.	3	1	2	75/mo.		Yes	
Emory Univ.[1] Emory University, Ga.	10	M.S.	10	2	2	900		Yes	
Fort Hays Kansas State Coll. Hays, Kansas	5	M.S.	4	2	2	450		No	0
Georgia Inst. of Tech. Atlanta, Ga.	6	M.S.	18	6	10	1200		Yes	2
Georgia, Univ. of Athens, Ga.	5	M.S.	8	3	3	700			2
Hawaii, Univ. of Honolulu 10, T.H.	3	M.S.	3	1	3	1300			
Kalamazoo College Kalamazoo, Mich.	1	M.A.	2						
Kansas State Teachers' Coll. Emporia, Kansas	3	M.A.	3	2	2	500		Yes	0
Laval University Quebec, Canada	7	D.Sc.	2	1	1	1000	1500	No	
Miami University Oxford, Ohio	6	M.S.	6	1	1	1100+		Yes	
Mississippi, Univ. of University, Miss.	6	M.A.	9	2	2	400	400	Yes	1
Montana State College Bozeman, Mont.	3	M.S.	7	1		1000			
Montana State Univ. Missoula, Mont.	3	M.A.	4	1	2	800		Yes	0
Nebraska, Univ. of Lincoln, Neb.	9	M.S.	10	4	8	1050		No	1
New York State Coll. for Tchrs. Albany 3, N. Y.	2	M.A.	4						
North Carolina State Coll. Raleigh, N. C.	2	M.S.	17	0	4	1000		No	
Occidental College[1,2] Los Angeles 41, Calif.	3	M.A.	3	2		800		No	1
Ohio University Athens, Ohio	3	M.S.	4	2	3	700+		No	
Redlands, Univ. of Redlands, Calif.	2	M.A.	3	2	1	800			
Rhode Island State College Kingston, R. I.	6	M.S.	8	2	2	1000		No	1

TABLE IV.—*Continued.*

Name and Address of Institution	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
Smith College Northampton, Mass.	5	M.A.	6	2	3	1025		No	2
South Dakota State College Brookings, S. Dakota	1	M.S.	2						
Texas Technological College Lubbock, Texas	2	M.S.	6	0	2	900		Yes	1
Trinity College[2] Hartford, Conn.	2	M.A.	4	2	2	800		Yes	
Tufts College Medford 55, Mass.	6	M.S.	12	2	3	800+		Yes	3
Utah State Agr. College[1] Logan, Utah	5	M.S.	4	4	4	75/mo.	100/mo.	Yes	1
Washington & Jefferson Coll. Washington, Pa.	2	A.M.	7	0	1	1200		Yes	
Wayne University Detroit, Mich.	8	M.S.	35	6	6	1000		Yes	
Wellesley College Wellesley 81, Mass.	2	M.A.	7	2	2	800+ −900+		No	
Wesleyan University Middletown, Conn.	8	M.A.	3	6	3	1300		Yes	3
Western Reserve University Cleveland, Ohio	5	M.S.	4	2	4	700 −800	900	No	
Williams College Williamstown, Mass.	7	M.A.	5	6	4	1200+	1500+	Yes	
Wyoming, Univ. of Laramie, Wyoming	9	M.S.	9	3	3	600 −800		Yes	2

[1] Predoctoral fellowship(s) or scholarship(s) also available.
[2] Graduate assistantships require approximately one-third time teaching.

M. Stipend in dollars for half-time research assistant possessing M.S. degree (including any fees that are waived).

See note after item *G*.

N. Are some appointments made with a different time distribution; for example, $\frac{3}{4}$ graduate study, $\frac{1}{4}$ assisting in research?

O. Does such research assisting count as credit towards an advanced degree? N, never; U, usually; S, occasionally.

Combination of graduate study and predoctoral fellowship

P. Total number of predoctoral fellowships available.

Some entries in the Tables give the number of fellowships that can be held in physics only; other entries include fellowships which, though tenable by students of physics, are also tenable in other fields in the same institution.

Q. Number of such fellowships available in September, 1949.

The notes following items *F* and *P* apply here.

R. Fraction of time spent in research (maximum).

S. Fraction of time spent in graduate study, excluding research (maximum).

T. Stipend in dollars attached to fellowship (range).

The note attached to item *G* also applies here.

U. Minimum degree required for appointment as research fellow.

V. Does such research count as credit towards an advanced degree? N, never; U, usually; S, occasionally.

Of 348 questionnaires returned to the Editor's office, 126 came from institutions where graduate work in physics is offered. Unfortunately, the list falls somewhat short of being a complete record for the United States. The information taken from the 126 questionnaires has been separated arbitrarily into four parts. Table I contains data concerning institutions where more than 50 graduate students are enrolled in the departments of physics; Table II, where the number of graduate students in physics lies in the range 26–50; Table III, where the corresponding number is from 11 to 25; Table IV, for 10 or fewer.—T.H.O.

Reproductions of Prints, Drawings and Paintings of Interest in the History of Physics

40. Vanity Fair Caricature of John Tyndall

E. C. Watson
California Institute of Technology, Pasadena, California

In 1869 Carlo Pellegrini, in the English *Vanity Fair*, began a series of portraits of public men that must be considered the most remarkable example of personal caricature ever attempted. The unextenuating likenesses of "Ape," as Pellegrini signed himself, were continued by "Spy" (Leslie Ward) and others until about 1910. In all, over 2000 portraits were published and many men of science of the period are to be found among them. On the whole the artists chose remarkably well and most of the scientists caricatured would be recognized even today as among the most outstanding of the period.

The likenesses were published with the purpose of providing "a permanent gallery of portraits of living men, drawn in their habit as they live, with their tricks as they move—not with a desire to caricature them, but with the desire to give the honest and brutal truth about them. . . . The attitude, the gesture, or the expression of face which often so cruelly epitomizes the man has been seized and recorded." Clever, observant to the point of mischievousness, but with caustic, penetrating and convincing truth, they show us better than written accounts can possibly do what these scientists were like as men and individuals.

Each caricature was accompanied by a tersely written account of the man portrayed. The writer, who signed himself "Jehu Junior"[1] states that "whatever else they may be they are honest; they have been written with the single object of telling the exact truth . . . there are no generalities in them nor any vagueness of purpose, because they represent distinct and clear conceptions. Every phrase rests upon the basis of fact, and is intended to have the full weight of its words and to suggest an opinion which the reader is left to work out for himself in the direction indicated." He says also regarding both the caricatures and the written accounts that "features are exaggerated which have the effect of stamping the personality more vividly on the mind than an ordinary portrait would do. A photograph, which gives every feature with absolute correctness, may yet fail to convey the distinct idea of character at which the artist and the writer have alike aimed."

Some of these caricatures have been reproduced, but to the best of my knowledge the written accounts have not. This is unfortunate as "the written account and the printed effigy are each the complement of the other" and should not be separated. Moreover, the written accounts are often very revealing, not of the mere facts of the subject's life—these are easily learned elsewhere—but of the attitude of the public of the time towards him and his work.

Among the scientists caricatured in this remarkable series are Thomas Huxley, Charles Darwin, John Tyndall, Lyon Playfair, George Biddell Airy, Richard Anthony Proctor, William Robert Grove, Louis Pasteur, Rudolf Virchow, William Thomson (Lord Kelvin), John William Strutt (Lord Rayleigh), William Crookes, William Huggins, Oliver Lodge, the Curies, William Ramsay, Robert Ball, Guglielmo Marconi, and many others. It would be interesting to reproduce all these caricatures in this series of historical reproductions. Unfortunately, however, the copyright laws prevent and so we must content ourselves for the present with reproducing during the next few months a few of the earlier ones.

John Tyndall (1820–1893) was probably better known to the general public during his own lifetime than he is today even among physicists. The friendly account, reproduced below, that accompanied his caricature, makes this clear, as does the excellent biographical sketch in the eleventh edition of the *Encyclopaedia Britannica*. It also shows the high regard in which science was held by the general public during the Victorian era.

[1] He was actually Thomas Gibson Bowles.

Professor John Tyndall, F.R.S.

"Science is before long to rule the world, and MR. TYNDALL is one of the pioneers of its kingdom. He is one of the most distinguished of that band of eminent men whose devotion to methods and subjects of research, by which the bases of prejudice are sapped, is by this time condoned, or on the road to condonation, by the children of prejudice themselves. He is an Irishman, and has the combativeness of his race; but he has its persuasiveness in a still larger measure, and though never known to decline a challenge, and generally victorious in the issue, knows the arts which make him a little less challenged than some of his brethren in the same pursuits. Only lately we have seen him, in the enthusiasm of friendship, exercising his rhetoric to convince the Philistine that MR. HUXLEY was less a foe to his tribe, and therefore better fitted for the London School Board, than had been commonly supposed. MR. HUXLEY and MR. TYNDALL are generally classed together in popular estimation in virtue of their approximate parity of years and standing in their respective pursuits, as well as of their high philosophical and literary ability and stirring ways in our midst. MR. TYNDALL is for Europe and America the representative of English chemistry and physics as is Mr. Huxley of English physiology; and Science is proud of both her sons. As an experimentalist and also as an expounder, the mantle of FARADAY is popularly understood to have fallen upon MR. TYNDALL, who succeeded to his place at the Royal Institution. There his lectures make the delight of young and grown-up audiences in a scarcely less degree than those of his famous predecessor, though the riotous spirits and self-conscious arts of the brilliant junior are very different qualities from the modest and absorbed simplicity of Faraday. It is in adding to the great discoveries of German *savants* concerning heat and light as modes of motion, the results of masterly original research and experiment of his own, that MR. TYNDALL's most characteristic fame as a leader of Science has been won. But he is a man of muscle, and a man of imagination, and a man of conversation, almost as much as a man of science; and it is these three gifts by which he is appreciated in unscientific circles, and at the hands of society at large. His muscle makes him so that he delighteth in his own legs; and he scales virgin Alps one after another, for the pleasure of the exercise as well as for the study of natural phenomena. His imagination makes him bring home fascinating accounts of these exploits, or sometimes, during the course of an excursion, takes to meditating on itself, with a result embodied in that famous lecture, which most people have read, on "The Scientific Use of the Imagination." Social habits have taught him also the scientific use of conversation, and he is one of the most welcome and expansive of table companions. In a word, whether in the laboratory where he conducts his investigations, whether in the theatre where he charms crowded audiences in

"The Scientific Use of the Imagination"
[From *Vanity Fair*, April 6, 1872].

showing off their results; whether on the peaks and passes where he risks his neck with so much enthusiasm, whether in the smoking-room of his club, whether in those corners of drawing-rooms where Birth and Beauty encircle Intellect in a sea of muslin and attention—PROFESSOR JOHN TYNDALL is a man at all times to be envied, and at nearly all to be admired."

DIGEST OF PERIODICAL LITERATURE

Degaussing

The simplest magnetic mines used by the Germans in the recent war were triggered by an increase in the vertical component of the magnetic field in which they were set. The operation of such mines could be prevented by a comparatively simple degaussing procedure. As the mines were made increasingly sensitive, degaussing had to become demagnetization, and had to be accomplished more and more accurately, taking into account the vertical, the longitudinal, and sometimes the transverse magnetization of the ship. This was accomplished by "deperming," "wiping," and "flashing" methods for overcoming permanent magnetization, and by the use of properly located coils carrying currents of considerable magnitude, for the neutralization of induced magnetism.

It was necessary to devise methods for measuring the results produced. In some cases measuring units were laid in line on the sea bed, each connected to a flux meter ashore, and the effects were noted as the ship moved over the instruments. Other magnetometers were slung under the ship and keel hauled from end to end. Such instruments proved to be sensitive, reliable, and rugged.

It was also necessary to provide the ship's magnetic compass with neutralizing coils to counterbalance the effects of the degaussing currents. In the latest stages of development, both degaussing currents and neutralizing currents for the compass were automatically controlled to suit the heading of the ship at the moment.

While degaussing was essentially a defensive procedure, it compelled the enemy to make his mines so much more sensitive that their removal by specially equipped mine-sweepers became much easier. H. CRAIG, "Degaussing," *Sch. Sci. Rev.* **30**, 38–52 (1948).—R. T. H.

Optical Sign Conventions

The convention for optical signs in most common use is the "real-is-positive" convention which associates positive signs with real objects and images, negative signs with virtual objects and images. While this convention may be simple to use in the most elementary work, it soon leads to difficulties, inconsistencies, and topsy-turvy conclusions which make it unsuitable for technical work. In the convention known as the "New Cartesian," the mirror, thin lens, or refracting surface is placed with its pole at the origin of Cartesian coordinates, and its optical axis coincident with the x-coordinate axis. Distances measured to the right are then regarded as positive, to the left negative, exactly as in the ordinary use of Cartesian coordinates in graphs. This system is at present used by few books, but it is shown to have very real advantages. The conclusion that the "real-is-positive" convention is far more complex in its full elaboration than the "New Cartesian" is inescapable, and if the final choice of a single convention is to be made there can be no doubt as to which it should be. The case against the "real-is-positive" convention is so strong as to overwhelm the mitigatory claims that have been made in its favor. O. DARBYSHIRE, "A critical survey of optical sign conventions," *Sch. Sci. Rev.* **30**, 58–68 (1948).—R. T. H.

There was nothing wrong with the old inference that if I know all about the present I can forecast the future exactly; the trouble was the impossibility of knowing the present. Once this is seen, the whole argument becomes obvious, but nobody saw it until Heisenberg.—C. G. DARWIN (1938).

NOTES AND DISCUSSION

A Simple Color Patch Apparatus

ROBERT WEALE
South-West Essex Technical College, Walthamstow, London, England

THE apparatus to be described can be set up in a few minutes by any person conversant with only the most elementary principles of optics. Its object is to demonstrate the mixing of colors in the class room. The fact that three separate beams are used enables the demonstrator to obtain white light by composition of primary colors.

Light from a powerful source (not shown in the diagram, Fig. 1) is focused on two slits S_1 and S_2. The former is horizontal, the latter vertical. Both are used with the achromatic lens combinations L_1 and L_2 to form images of the corresponding slits on a distant screen E. In front of L_1 there is a prism with its refracting edge in a horizontal direction. A spectrum is produced on the screen E by means of an adjustable mirror M_1 which deflects the beam in a vertical plane.

In front of the lens L_2, there are two identical prisms which divide the light coming from S_2 into two equal parts. These refract the two parts of the beam in opposite directions, since their refracting edges are on opposite sides of the axis of the system. Thus it comes about that the mirrors M_2' and M_2'' produce on the screen E two spectra arranged in opposite directions. By suitable adjustment of the mirrors, which are free to turn about vertical axes, any two colors can be made to coincide. In particular, such coincidences can be effected in the plane of the beam coming from S_1. New combinations can be produced when the latter beam is mixed with any two colors of the horizontal spectra. The relative intensities of the colors can be varied by means of slits T_1, T_2', and T_2''. Although the wavelength distribution of the colors is varied by changing the slit-widths, it is felt that the smallness of the error does not warrant the use of a rotating sector or other control independent of the wavelength. It should be borne in mind that one of the spectra is vertical, so that it can be used as a kind of "scanning" device, greatly facilitating the detection of the white point. Scanning is produced by turning the mirror M_1.

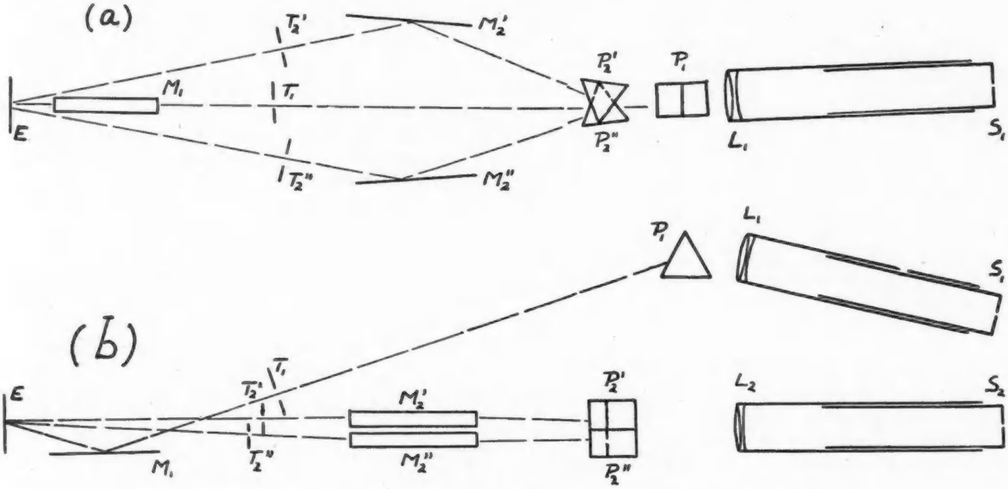

FIG. 1. Showing (a) plan and (b) elevation of a simple color patch apparatus for demonstration.

In actual demonstrations, spectra of 1.5 in. height were used. While good mixing effects were obtained without the use of slits the latter were necessary in the production of the white spot. Without them the neighboring colors gave rise to contrast which made the detection of the white spot possible only with great difficulty.

We must never forget that metaphysics divides people, and science unites them.—PHILIPP FRANK.

LETTERS TO THE EDITOR

The Brooklyn College Student Opinion Report

TEACHERS of physics who are proud of the student opinion of good teaching in science might be shocked by the recently published report on "Student attitudes and opinions relating to teaching at Brooklyn College."[1] This letter to the editor is not to give a review of the findings, but to ask fellow teachers of physics the reason for the students' rank of science in one respect. The order of frequency of the four qualities in teachers most desired by the students is shown in the following lists:

	Percent	Rank Order
In Arts		
Knowledge of subject	54	1
Encouragement to thinking	47	2
Attitude toward subject	46	3
Ability to explain	42	4
In Social Science		
Encouragement to thinking	70	1
Organization of subject matter	48	2
Tolerance to disagreement	45	3
Knowledge of subject matter	42	4
In Science		
Ability to explain	89	1
Organization of subject matter	78	2
Knowledge of subject	70	3
Encouragement of thinking	17	4

Do teachers of science admit that the relatively low ranking of "encouragement of thinking" for the science instructor[2] is inherent in the subject? If not, what is the matter with our teaching?

Another part of the report is also worthy of reflection. The students prefer an approach which places emphasis upon ideas rather than upon facts in arts and in social science, indeed, 85 to 13 percent in both cases. In science there is just the reverse vote, 85 percent favoring emphasis upon facts and only 13 on ideas.

It is to be hoped that teachers of physics will be disappointed in this opinion of 6681 students of Brooklyn College. Does it not suggest a reflection on the educational value of science to nonscience students? What can we do about it?

State University of Iowa, Iowa City, Iowa G. W. STEWART

[1] Goodhartz, School and Society **68** (No. 1769), 345 (1948).
[2] These findings should be regarded as of general application, irrespective of institution.

The Student's Facility in American Prose

THE article by Pearl I. Young in the November issue of the *American Journal of Physics* on how the physics teacher can help improve student writing presents a rather distorted view of the subject. For one thing, nowhere is there any reference to the fundamental reasons why undergraduates write badly. It is little wonder then that the proposed solution to the problem is inadequate.

The remark that the student "follows the style of college textbooks" betrays an astonishing unfamiliarity with the facts. The style of the college textbook may seldom rise above a pedestrian level but, in the physical sciences at least, it is normally precise and orderly, the very antithesis of typical undergraduate prose. If the physics teacher is really to make a contribution in this field, it might be well to have the discussion continued by those whose experience has been in the classroom rather than the editorial office.

Indeed the article as a whole exhibits a preoccupation with the minutiae of the editorial function along with an unrealistic attitude toward matters of English usage. The The futility of this hypercritical approach to details of grammar and sentence structure can not be more effectively illustrated than by the following specimen. In the same column (p. 428) in which she warns the unwary about using pronouns with "vague antecedents" Miss Young writes: "Do the 'apparatus and procedure' parts of the students' laboratory reports come up to the standards of *those* in English composition?" The pronoun *those* has no antecedent at all, in the usual sense of that term, and yet the sentence is sufficiently clear.

It is time we abandoned the methods of eighteenth century purists and learned how to deal with language problems from the point of view of twentieth century linguistic science. Would it not be most appropriate for a journal published for a scientific audience to lead the way?

Pennsylvania State College, State College, Pennsylvania H. DAVID RIX

THE COMMENTS of Dr. H. David Rix on my paper in the November *American Journal of Physics* are all very well taken. It may be possible to present all the angles of the very debatable question concerning the coordination of English composition with other college subjects in a short paper but I am not clever enough to do it.

I tried to safeguard myself in the Introduction and Summary of the paper by the statement of a simple thesis: At the same time the physics teacher is fulfilling his *primary* function of presenting the principles of physics, might he not consciously attempt to exemplify the principles of English composition that are being taught the student during the same college years?

In the part of my paper to which Dr. Rix takes particular exception I had intended "those" to mean sections on "Apparatus and Procedure" as taught in English composition. Our students have assignments in both these fields; they are required to describe a piece of apparatus or a device and also to outline the steps in a procedure. It is considered quite the thing in English composition for our science students to describe a vernier caliper and outline the procedure for determining the value of Young's modulus. Even in speech class, they borrow physics material

when they are assigned a topic that requires demonstration equipment.

The American Association of Teachers of English has gone a long way in throwing overboard the methods of eighteenth century grammatical purists and, as a whole, the modern composition books are surprisingly liberal. They permit as passable practically all of the borderline cases of current debatable usage that appear in any reasonably edited periodical. One must, of course, be constantly on the alert when reading cultured authors to note which additional phrases or usages have passed over into the acceptable area. In my opinion, a considerable amount of graduate effort in the obtaining of master's degrees in English could well be spent in analyzing such debatable forms and recommending action on acceptance or rejection of forms as well as the changing connotation of words. In any such analysis, the advice and opinion of writers and readers of college textbooks in all fields including science and engineering would be invaluable to the English department.

The sort of thing I had in mind—in addition to the use of words, symbols, forms, etc., specifically adopted by our professional societies—was the guarding against usages that have not been accepted in any carefully edited periodical. As one isolated example, one current writer of physics textbooks consistently uses "further" for "farther," although he does not go to the extent of writing "How fur does the car travel in 2 seconds?" I have heard men lecturing from his textbook repeat the error and ask "How much *further* does the first car travel in one second?"

The question of whether the English departments are teaching the students a grade of pedantic, out-of-date, nonfunctional English composition is, I presume, the province of the Deans and the administrative officers. The type of advice given in courses in Technical Writing is, of course, of interest to all workers in science and engineering.

It cheers me a great deal to know that many colleges are making an effort to coordinate the teaching of English with the teaching of physics. On the other hand, one hears of schools where the rule in grading papers is to pass any errors in spelling, punctuation, composition—whether it be chemistry, physics, art, or history—as long as the instructor can extract the subject matter. In fact, individual teachers who persist in marking errors in such matters have been waited on by student groups, and not with praise. Because I do not think it is fair to a scientific student to let him slip into careless habits of composition, just when he has been set on the right road, I correct all errors in spelling, punctuation, form, composition but grade the papers solely on their scientific merit.

Pennsylvania State College,
Schuylkill Undergraduate Center,
Pottsville, Pennsylvania

PEARL I. YOUNG

A Simple Mnemonic for Maxwell's Thermodynamic Relations

IN a recent communication,[1] Mr. Charles Focken mentioned the difficulty of remembering Maxwell's thermodynamic relations, and asked what mnemonics others had found helpful in working with them which might be better than one which he described. I would like to suggest a device which seems to me to be natural and very easily retained.

Essentially, Maxwell's equations say that certain partial derivatives, involving members of the quartet (T, S, V, P), may be replaced by certain other partial derivatives, formed from the same quartet. The trick of remembering them boils down to that of remembering what kind of partials can be replaced and what the rule of replacement is.

This trick is simple if we think of the familiar expressions PdV and TdS, which naturally pair off the quartet into the pair of "mates" P and V and the pair of mates T and S.

Any partial appears in Maxwell's relations if it is of the form $(\partial T/\partial P)_S$ where the numerator and the subscript are mates. They may be of either pair in either order. The denominator may be either member of the other pair.

The replacement is obtained if we write the missing member of the quartet as a dummy superscript on the upper right and then interchange the right and left hand columns:

$$(\partial T/\partial P)^V{}_S \rightarrow (\partial V/\partial S)^T{}_P.$$

The sign of the replacement is positive if numerator and denominator are either both intensive or both extensive co-ordinates. Otherwise it is negative. In the example, since T and P are both intensive, the sign is positive.

The dummy superscripts may be carried in one's head after a little practice, so that the transformation is made at sight.

University of North Carolina,
Chapel Hill, North Carolina

W. E. HAISLEY

[1] *Am. J. Physics* **16**, 450 (1948).

FOCKEN has indicated in a recent note[1] that the derivation of the four Maxwell relations

$$(\partial P/\partial T)_V = (\partial S/\partial V)_T \quad (1)$$
$$(\partial V/\partial S)_P = (\partial T/\partial P)_S \quad (2)$$
$$(\partial P/\partial S)_V = -(\partial T/\partial V)_S \quad (3)$$
$$(\partial V/\partial T)_P = -(\partial S/\partial P)_T \quad (4)$$

is "laborious and not especially easy." Although numerous "laborious" derivations are given in some common textbooks[2] the following derivation appears to meet Focken's desire for a short derivation and for a derivation which gives the required reciprocity relation without deriving all four.[3]

It is very useful in thermodynamics to associate the following variables:

$$U \text{ with } (S \text{ and } V) \quad (5)$$
$$H \text{ with } (S \text{ and } P) \quad (6)$$
$$A \text{ with } (T \text{ and } V) \quad (7)$$
$$G \text{ with } (T \text{ and } P), \quad (8)$$

the symbols having their usual thermodynamic meaning. By using the first and second laws of thermodynamics

together with the Legendre transformation and the definitions of U, H, A, and G, we can easily see the basis for this association:

$$dU = TdS - PdV \tag{9}$$

$$\frac{d(PV)}{dH} = \frac{VdP + PdV}{TdS + VdP} \tag{10}$$

$$dH = TdS + VdP$$

$$\frac{-d(TS)}{dG} = \frac{-TdS - SdT}{VdP - SdT} \tag{11}$$

$$dU = TdS - PdV$$

$$\frac{-d(TS)}{dA} = \frac{-TdS - SdT}{-PdV - SdT}. \tag{12}$$

Having obtained these extremely valuable relations very simply we need now only apply Euler's condition for an exact differential to (9), (10), (11), and (12), and the reciprocity relations result. For example from (9) we obtain $(\partial T/\partial V)_S = -(\partial P/\partial S)_V$.

If a particular relation is required one need not derive (9), (10), (11), and (12), but only the particular relation which leads directly to the desired relation. This can be done by keeping in mind the above mentioned associations.[4] These associations are not difficult to remember since (5) is the simplest combination of the first and second laws; (6), the simplest example of a transformation of variable (can be done mentally); (8), an association which is repeatedly stressed in chemical thermodynamics; and (7), an association which can be obtained from the symmetry of the variables and the fact that only variables S, T, V, and P are involved in the relations. For example, if we wish to obtain the Clausius-Clapeyron equation (after careful interpretation of the reciprocity relation) we want the relation involving $(\partial P/\partial T)_V$. Since T and V are the independent variables in this case, we associate them with the function A and derive (12) and the required relation follows directly.

Since the derivation given above is so simple, it seems that a mnemonic is quite unnecessary in this case. However, since there appears to be a need for such a device the following one, based on the above ideas, is offered. With this device one can write down any one or all of the relations immediately without derivation. In addition to an elementary knowledge of thermodynamics, it is only required that one remember the following facts:

1. Only the variables S, T, V, and P are involved in the reciprocity relations. The pair of independent variables (considering only those systems with two independent variables) occurring in a given reciprocity relation is the pair associated with any given property in (5), (6), (7), and (8). This follows directly from the derivations as given above.

2. The reciprocity relations give no information concerning the variation of entropy with temperature or its reciprocal. This is easy to remember since it brings to mind immediately the very important relations $(\partial S/\partial T)_V = C_v/T$ and $(\partial S/\partial T)_P = C_p/T$.

3. Whenever T and P occur on opposite sides of the equation as derivatives, a negative sign must be appended to one side.

A common use of the reciprocity relations is in the elimination or transformation of certain expressions in other derivations. For this purpose a given partial derivative is known, for example, $(\partial S/\partial P)_T$, and it can be ascertained immediately if one of Maxwell's relations applies and if it does, exactly which one does apply. In the example given, since P and T are the independent variables, the remaining variables must be S and V (by rule 1) and since P and T will occur on opposite sides of the equation, a minus sign must be appended (by rule 3). We therefore obtain relation (4). If it is desired to obtain all four relations we use the above associations and form one relation from each pair of variables associated with the given property, using the pair of variables as the independent variables (occur in the denominator of the relations and indicate what is being held constant), and the remaining variables in each case as the dependent variables (occur in the numerator of the relations) and apply the rules given above.

This device has been found to be quite useful and easily remembered, perhaps because it places more stress on an extension of fundamental thermodynamic ideas and less on mnemonic paraphernalia.

Western Reserve University,
Cleveland, Ohio
JOHN BUGOSH

[1] *Am. J. Physics* **16**, 450 (1948).
[2] See for example, P. S. Epstein, *Textbook of thermodynamics* (Wiley, 1937), p. 64; and Lewis and Randall, *Thermodynamics and the free energy of chemical substances* (McGraw-Hill, 1923), p.133.
[3] This derivation was first indicated to the author by Mr. Charles H. Fletcher, now of Princeton University.
[4] It is useful to remember these associations only because of the relations (9), (10), (11), and (12) which serve as a starting point for many derivations.

A Simple Concept of the Einstein Photoelectric Equation

IN a core course in physics it seems desirable to include some discussion of the photoelectric effect inasmuch as many commonplace devices utilize this phenomenon. It is, however, often difficult to convey to these students, untrained in algebra, the meaning of the Einstein equation. This difficulty may be obviated by an example in which we regard the electrons as bricks in a building. The incident radiation then is a ping pong ball or a cannon ball, depending upon the wavelength (energy). Obviously a ping pong ball has little effect upon impact. A cannon ball (short wavelength) is sufficiently energetic to knock out a brick whose kinetic energy then depends upon two things: how much energy the cannon ball imparted, and how much of that energy was used in getting the brick free. The corollary must be limited by stating that one cannon ball affects one brick only. The author would be glad to hear how other teachers have presented this topic to students lacking mathematical training.

Colorado A. and M. College,
Fort Collins, Colorado
NORMAN STEVENS

RECENT MEETINGS

Michigan Teachers of College Physics

The Michigan Teachers of College Physics met at the University of Michigan, Ann Arbor, Michigan on Saturday, November 20, 1948. Approximately 100 teachers of physics from Michigan colleges and universities attended the morning sessions in the West Physics Building. Dr. E. F. Barker presided over the session. A program of nine contributed papers was presented.

1. Small spherical particles of exceptionally uniform size. R. C. WILLIAMS, *University of Michigan.*—An old latex suspension was observed to have particles of remarkably uniform diameter 2590±25A. Scattering experiments using the suspension showed unusual color selectivity.

2. The use of vector methods in deriving some formulas in mechanics. KEITH R. SYMON, *Wayne University.*—Radial and angular components of vector velocity and acceleration were derived. By using these the Coriolis acceleration was expressed in its radial and angular terms.

3. An attempt toward more wisdom and less knowledge. RICHARD SCHLEGEL, *Michigan State College.*—An experimental course for non-science students given at Princeton University was described. The purpose was to give students an intensive coverage of a restricted group of topics in elementary physics.

4. Shock waves. CHARLES W. MAUTZ, *University of Michigan.*—Experiments performed in a shock tube used as a supersonic wind tunnel showed air speeds corresponding to Mach numbers as great as 2.4.

5. Absorption cells for vacuum spectroscopy. ROBERT H. NOBLE, *Michigan State College.*—Gas absorption cells for use in the evacuated infra-red spectrometer were described. The cells were constructed of aluminum tubing and used rock salt plates over their ends to permit passage of the radiation.

6. Attenuators and pads. JAMES A. RICHARDS, *Olivet College.*—Design of *T*, *H*, and *L* attenuation pads for radio work was explained. A simple form of *T* pad requiring only one variable control was described.

7. A demonstration of banked curves. EVERETT HAYNES, *Highland Park Junior College.*—A demonstration showing the relationship between banking angle, radius and speed of vehicle was performed.

8. Simple equipment for an experiment on moment of inertia. THOMAS H. OSGOOD, *Michigan State College.*—An apparatus used in the elementary laboratory for measurement of rotational inertia and having numerous advantages over commercially available equipment was demonstrated.

9. Velocity of a compressional pulse. WILLIAM W. SLEATOR, *University of Michigan.*—The expression for the speed of a pulse in terms of the elasticity and density of a gas was derived from consideration of the motion of the pulse produced by a piston moving at constant speed along a tube containing the gas.

Luncheon was served at the Michigan League. Dean R. A. Sawyer spoke briefly at the luncheon upon the problems involved in the education of college teachers. Dr. Thomas H. Osgood presented a communication from the Michigan Academy of Science. The afternoon was occupied by a visit to the Willow Run Airport, at which the U. S. Weather Bureau Station, the control tower, and the University of Michigan wind tunnel were inspected.—B. H. D.

Illinois Section

The annual fall meeting of the Illinois Section of the American Association of Physics Teachers was held at Eastern Illinois State College, Charleston, Illinois on November 5–6, 1948. Thirty-three Association members from twelve colleges and one commercial company attended the sessions. Many of the members were overnight guests of the College, which this year celebrates its Fiftieth Anniversary. Entertainment was provided for wives of members attending the meeting. Arrangements for the meeting were under the supervision of Dr. Glenn Q. Lefler, Chairman, Program Committee and Dr. O. L. Railsback, Head, Physics Department.

Three hundred and ninety persons attended the open meeting on Friday evening in the Auditorium of the Health Education Building. Dr. Robert G. Buzzard, President of Eastern Illinois State College, welcomed the members and guests of the Section to the host institution. Dr. Railsback introduced the speaker, who presented an invited paper:

A theory of solar origin of cosmic rays. WINFIELD W. SALISBURY, *Collins Radio Company, Cedar Rapids, Iowa.* Evidence supporting a theory of the origin of cosmic rays from acceleration of ions in free space by very long radio waves originating in ion flow in the sun's atmosphere was examined by the speaker. The address was illustrated by motion pictures of the sun's corona showing the turbulence of hydrogen gas in the sun's atmosphere. The film was taken by means of the newly developed technique of an artificial eclipse, using a sharp, hydrogen-line filter.

An informal social hour followed the evening session. The Saturday morning sessions were held in the Science Building. Dr. Lefler presided over the sessions. Four contributed papers and a symposium constituted the program.

Contributed Papers

Why the common type of a.c. ammeter reads what it does when carrying both a.c. and d.c. W. H. ELLER, *Western Illinois State College.*

The combining of simple electronic instruments into a "Z" meter and its use in studying characteristics of radio equipment. O. L. RAILSBACK, *Eastern Illinois State College.*

Use of the automobile transmission as a quantitative group experiment in first-year general physics. ROBERT C. WADDELL, *Eastern Illinois State College.*

The present and the future in television in Illinois. HOWARD HACKETT, *Terre Haute Radio Company.*

Symposium

Topic: The place of the new material in the fields of electronic and atomic physics in the undergraduate physics program.

The problem of introduction of the new material into the undergraduate program; (a) the organization of the new material in the courses (b) the selection and development of equipment to be used in the courses. JACOB A. RINKER, *Eureka College.* The problems presented by adding the new material to an already full program were pointed out. A call for re-evaluation of the total content of undergraduate physics courses was issued.

Possible use of field trips; for the student, for the teacher. ROBERT F. PATON, *University of Illinois.* The importance of making arrangements ahead of time for field trips was stressed. Maximum gain accrues to the student when preparations are made ahead of time by the institution or plant visited.

Possibilities and limitations of the undergraduate work in electronic and atomic physics as viewed from the research laboratory. G. D. ADAMS, *University of Illinois.* Making the undergraduate physics program give training in accuracy and self-discipline as prerequisites to the responsibilities required in research were goals cited by the author.

A recess during the morning session gave opportunity for inspection of the contributed exhibits and the Physics Laboratories. At the noonday luncheon a brief business session was held. The Section was invited to the University of Illinois for the 1949 annual meeting.

GLENN Q. LEFLER,
Chairman, Program Committee
O. L. RAILSBACH,
Representative, Illinois Section

ANNOUNCEMENTS AND NEWS

Book Reviews

Nuclear Radiation Physics. R. E. LAPP AND H. L. ANDREWS. Pp. 487. Prentice-Hall, Inc., New York, 1948. Price $6.00.

Undergraduate physics is again experiencing a revitalizing period of natural selection. As a result of the demands made by the war in the applications of physical knowledge developed during the preceding decades, electronics, atomic physics, acoustics and nuclear physics are receiving increased emphasis in college curricula. No longer is it necessary to justify the study of these subjects to the more practical-minded student. As a result, nuclear physics is becoming an essential ingredient in the undergraduate program of liberal arts colleges. In technical colleges nuclear physics is rapidly replacing more classical scientific subjects. Consequently, there is real need for good textbooks at the junior-senior level. *Nuclear Radiation Physics* by Lapp and Andrews should help a great deal in satisfying this demand.

The authors have certainly achieved their purpose of presenting a logical and simple interpretation of the phenomena of nuclear physics. Although the approach is essentially nonmathematical, all the fundamental equations are included and numerous illustrative examples of their application are worked out in detail. The authors have wisely chosen not to follow the historical approach. Instead, descriptions of significant steps in the development of nuclear physics are sprinkled throughout the text—adding flavor without undue emphasis.

The first three chapters of this book cover the elements of wave and particle motion and serve as an introduction to atomic structure, natural radioactivity and nuclear structure, presented in a concise and crystal clear summary in the next three chapters. The review of alpha-, beta- and gamma-rays emphasize the interactions of these radiations with matter. Working curves of range *vs.* energy are included for alpha- and beta-particles. An absorption curve for gamma-rays in lead is supplemented by an appendix which contains tables of the absorption coefficients of the more common elements and of important shielding materials. Since all nuclear-radiation detection techniques depend upon ionization, the three chapters on methods of measurement can be included at this stage in the development without slighting the neutron, to which a later chapter is devoted.

The chapter on artificial radioactivity is largely a summary of particle accelerations. The content is sufficiently up-to-date to include general considerations of the f-m-cyclotron, the betatron and the synchrotron and to call attention to the recently announced bevatrons to be built at Brookhaven and Berkeley. It is also refreshing to find that the following chapter on nuclear reactions, in addition to covering all of the familiar types, also includes those produced by tritium together with a summary of the

high energy reactions obtained at Berkeley. Additional indications of the efforts exerted by the authors and publisher to have the book up-to-the-minute are the references to current literature through July, 1948 and the famous photograph of the first artificial meson obtained by Gardner and Lattes. The chapter on nuclear fission provides an adequate introduction to the general discussion of the nuclear chain reaction. Two bits of information not previously declassified appear. The chapter on radioactive tracer techniques constitutes a concise review of the more pertinent problems. The table of commonly used radioisotopes includes ranges and dosage rates of the radiations. Additional data are tabulated in an appendix. The concluding chapter briefly reviews radiation hazards and health physics. Practical precautionary procedures and methods of decontamination and disposal of radioactive wastes are given in another appendix. There is also a tabulated list of radiation instrument manufacturers.

The book contains additional features of particular value to the student and teacher. Almost every page includes an informative photograph or diagram. It is obvious that these have been carefully selected for their direct bearing on the discussion, since all unnecessary details have been omitted. At the end of each chapter there is a sizable list of problems. Most of these simply require a straightforward application of the material in the chapter. However, a few require real ingenuity for an exact solution. References are also included at the end of each chapter. Some are general in scope, but most of the references are to current literature and provide a ready guide to most of the important source material on which the chapter is based. This book is an excellent addition to the Prentice-Hall Physics Series edited by Dr. Donald H. Menzel of Harvard University.

CLARK GOODMAN
Massachusetts Institute of Technology

The Elements of Physics. Fifth edition. ALPHEUS W. SMITH. Pp. 745+xvi, Figs. 917, 23×15 cm. McGraw-Hill Book Company, Inc., New York, 1948. Price $5.00.

As I sit down to record a few remarks concerning Professor Smith's new fifth edition of *Elements of Physics*, a glance at my bookshelf reveals twenty-seven different textbooks having various titles but all dealing with college physics at the introductory level, and these represent only a portion of the volumes now in print by various publishing houses. Some are well known and widely used, others are entirely new and untried. A few are new editions precipitated by recent developments in nuclear physics, the only essential modification being the insertion of a frontispiece showing an exploding atomic bomb and an additional paragraph at the end of the last chapter *explaining* the nature of atomic fission. None of the elementary books on my shelf are fifth editions and none have been in use for twenty-five years. Indeed, it is probably safe to say that few of them will survive for a quarter of a century. Without reference to, or analysis of, the content of *Elements of Physics* one can say that its continued use and popularity for over a quarter of a century are lasting tributes to the author as a great teacher.

The factors governing the adoption of a particular book for classroom use are varied and many. In some cases there seems to be no apparent reason for selection other than the fact that certain neighboring institutions of established reputation have done so; it is a case of climbing on the band-wagon without knowing what is being played or where the parade is headed. I think it is safe to say that not many teachers are completely satisfied with any textbook. Some may object, as I did, to certain parts of *Elements of Physics*. It seems to me, for example, that one should (1) use a dynamical definition of force, (2) acquaint the student with the addition of vectors by the summation of components method, (3) avoid ambiguous use of emf, voltage, and difference of potential, (4) define temperature in terms of the direction of heat flow and the molecular kinetic energy of a body, (5) omit the hydraulic analog in electric circuit analysis, (6) justify Kirchhoff's Second Law in terms of energy, and (7) give the presently accepted values of certain well known physical constants such as e. Examination of any textbook from a particular viewpoint will uncover similar objections. One must, of course, weigh the good against the bad. It is probably fortunate that not many teachers have enough time to be supercritical. Otherwise we should have even more books on general physics. Much more could be said concerning factors which influence the selection of a particular textbook. As a matter of record it should be said that the judgment of a reviewer who has not used the book in class would be of secondary importance.

Physics is an ever expanding field of knowledge and the applications to technology, industry, medicine, and other branches of science are growing at a rapid rate. It is natural that a physicist should wish to have it known whence these developments have stemmed and the basic physical principles upon which they rest. As the author of a basic text designed for an introductory course, however, he should keep in mind the customary amount of time allowed in the student's schedule for such a course. A serious effort should be made to include an amount of material which can be reasonably covered in the course for which the textbook is designed. The present tendency seems to be to keep adding new topics and new illustrations of applications in this field and that. This is not a criticism directed solely against the volume under review. It is a characteristic of practically all the serious textbooks in the field of introductory college physics. From the standpoint of the student an over-stuffed book is an avoidable irritation. He is confused by the diversity of the material and dissatisfied with the necessarily superficial treatment given many topics. Teachers will agree that basic principles should be given and that they should be added to new editions when they occur as new developments in the field of physics. Would it not be better to omit or delete much of the material relating to special applications realizing that the student will master these in his further work in engineering or in advanced courses in physics?

VERNON L. BOLLMAN
Occidental College

College Physics. Third edition. NEWTON HENRY BLACK. Pp. 800. Figs. 697, Pl. XXII, Tables 36, 22×14 cm. The Macmillan Company, New York, 1948. Price $4.75.

The reception which has been accorded the two earlier editions of this text indicates a wide recognition of its virtues. It is written for college freshmen and others of limited mathematical background who do not expect to continue in the pursuit of physical science. To this end the material is presented in a simple, direct style which strives at every point to avoid the use of unfamiliar terminology which might discourage the student. The inevitable difficulty of introducing the student to new and unfamiliar principles and terms has, in most cases, been handled unobtrusively by well chosen analogies and a gradual advance from familiar things.

In some respects, however, the author seems not to have been very successful. It is to be regretted that the preparation of the third edition was not seized as an opportunity to remedy the shortcomings of the earlier ones. Admittedly, some of the statements with which the reviewer disagrees are controversial. However much one may abbor the use of $F=(w/g)a$, the last word has apparently not been said on the subject. On the other hand, the difficulty of explaining quickly how the acceleration of gravity gets into centripetal force should discourage any teacher from writing $F=(w/g)(v^2/r)$. It seems hard to justify this practice except on the basis of the constitutional guarantee of freedom of speech. If the concept of mass has virtue at all, it would seem that no better place could have been found to apply it. But it should have been introduced before the confusion of $(w/g)(v^2/r)$ had entered the mind of the student.

There are, at various points in the book, statements which are definitely misleading. These are probably due to an assumption on the part of the author that accuracy must be sacrificed for the sake of simplicity. That he willingly makes such sacrifices is illustrated by the statement, "it is evident that centripetal force depends on three factors, weight, speed, and radius of curvature." The student who is told on p. 163 that centripetal force depends on weight, and is then told on p. 170 that "The weight of a body is a force acting on it, not a description of what it contains," can hardly be blamed for being confused regarding the role of the force of gravity in centripetal force. Moreover, is it not undesirable to include the term speed, a scalar quantity, in a statement regarding a force whose very existence depends upon the change of direction of velocity?

In the discussion of condensers in series, on p. 387, this statement occurs: "The practical advantage of the series arrangement is that it offers great dielectric strength." The same statement occurred in the second edition. It is, of course, simply misleading. Every physicist knows what the author meant, but the student may well wonder how dielectric strength can depend on the mode of connection of condensers.

On p. 375, Millikan is given credit for measuring the charge and the mass of the electron. On p. 260, the student is presented with what seems to be a confused "Theory as to what heat is" as follows:

> "There are many reasons for thinking that heat is a rapid vibratory motion of the molecules of substances or of the space between the molecules. . . . We imagine that this molecular vibration extends to the surrounding space and thus is sent out in straight lines in all directions as radiant energy."

Again, only a physicist could know what the author was trying to say. A student would be puzzled.

On p. 270, the caption below Fig. 14–4 indicates that it is a "Curve showing heat required to change 1 gram of ice from −40°C into steam at 120°C." Actually, however, the "Temperature in °C" is plotted *versus* the "Time in minutes" which is, of course, completely meaningless unless the rate of application of heat is specified—which is not the case in either the figure or the accompanying text material.

Here and there the order of presentation and the emphasis could have been improved. This criticism may be illustrated by the discussion of the Van de Graaff generator. Following the description of constructional features and the manner in which the belt is discharged inside the metallic terminal the student is told "Then the charge is distributed on the outside of the terminal." There is no indication of the manner in which this occurs and the author immediately goes on to describe the rise of potential and ultimate discharge. The next paragraph, in fine print, gives a brief description of the Faraday ice pail experiment but nowhere is there any intimation of a relation between this and the Van de Graaff generator. Surely the description and discussion of the ice pail experiment should precede rather than follow the explanation of the generator.

Its virtues do not set this book apart as an extraordinary contribution to the field of college physics textbooks. They are of the sort a teacher would have a right to expect. To enumerate them here would be merely to simulate an advertising prospectus. Mention should be made, however, of the author's contribution toward the solution of a perennial problem in the teaching of physics, regarding the existence of which many teachers would agree. This is the tendency of students to regard learning as a process of memorizing formulas. The author remarks in the preface that:

> "Our experience has shown that students are too apt to memorize equations, thinking that the study of physics consists of remembering the right equation and substituting the right numbers for the letters."

He has sought to discourage this tendency by emphasizing word-equations and concise verbal statements of basic principles. Complete elimination of algebraic expressions is neither desirable nor feasible and the author seems to have followed the best possible middle course.

FRANK E. HOECKER
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Atomic Energy. Karl K. Darrow. Pp. 88. John Wiley & Sons, Inc., New York, 1948. Price $2.00.

This book contains four Norman Wait Harris Lectures given by Dr. Darrow at Northwestern University in 1947. To this fact of oral presentation the book may owe much of its beautifully lucid style. The tone of voice is a conversational one; the presentation provides a smooth narrative; the net effect is thoroughly delightful and might well provide a model for lecturers.

The task of one who seeks to lead the uninitiated through the field of nuclear phenomena is not easy. In Dr. Darrow's words, "in 1913 . . . we were like tenants in a sturdy old-fashioned apartment house (*i.e.*, the house of physics) which somebody else had put up;" whereas now "the house has become very strange. It is much grander than ever before, . . . of a modernistic style which has a freakish look to all but those who built it and those who are bred to it, and we have the uneasy feeling that there is a high explosive lurking somewhere near the furnace." Nevertheless, the author engages upon a tour of the house with an ease and clarity which belie his fear of a "chaotic mental image" on the part of his audience at the end of the first lecture. Not the least element in his success is an economy of attention which had avoided getting off onto intriguing questions which would require too much investment for any return in understanding. Thus, in dealing with the question of the stability of the heavy nuclei, the question is raised as to why alpha-decay of the polonium nucleus does not take place immediately upon creation of the nucleus. No more is said on this point than that "it is a secret. Not . . . a military secret, but what I may term a quantum-mechanical secret, veiled from all but . . . the initiates."

Another element in the readability of the book is its anthropomorphic personalization of nuclear phenomena, in a manner which no one should consider beneath his dignity. Thus, the beta-decay of a radioactive nucleus is described by saying: "Such an unhappy nucleus adjusts itself to its desire (*i.e.*, the previously discussed optimum neutron-proton ratio) by spontaneous conversion of a neutron into a proton."

A general idea of the emphasis of the book may be obtained by running through the contents of the four lectures. The first deals with atoms, electrons, nucleons, ending with the "pretty pickle" of the mass defect of the deuteron. There follows in the next lecture an exploration of the binding of nuclei, the mass-energy relation, and nuclear transmutations such as occur in the bombardment of deuterons with deuterons. (Here, it is emphasized, a high-voltage accelerator acts *not* as an "atom-smasher" but rather as a beneficent agency bringing dissatisfied deuterons close enough together so that the component nucleons may rearrange themselves more according to their own inclinations.)

The third lecture concerns itself with more transmutations, with alpha- and fission-instability, and with the suddenly disturbing conclusion that the gold in Fort Knox has no real right to be there since a gold nucleus would release energy if it were suddenly cut in half with a super microtome. The fission of uranium and its suggestion of a Wagnerian *Gotterdämmerung* leads into the final chapter, with its description of the chain-reacting piles, radioactivity, and the hopeful use of radioactive nuclei as tracers.

Perhaps in order to keep a favorable review from sounding like paid advertising the reviewer should pick a few faults. This seems rather inappropriate here; as an enjoyable and intriguing introduction to nuclear phenomena for the non-physicist, and as a demonstration of good pedagogy for the physicist, this book is highly recommended.

D. R. Hamilton
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A Textbook of Heat. LeRoy D. Weld. Pp. 436+x, Figs. 130, Tables XVIII, 14½×21½ cm. The Macmillan Company, New York, 1948. Price $5.00.

This text comprising eleven chapters is based upon material which the author has used as lecture notes in a course in heat for juniors and seniors over the past thirty-five years. Although described by the author as "new and up-to-date," many of the figures and much of the general treatment are characteristic of the earlier part of the above-mentioned period. This is perhaps to be expected, for most of the simpler parts of the subject were well worked out and correctly interpreted many years ago.

There can be no doubt that a student who has mastered all the presentations in the text would have a considerable knowledge of the subject of heat. Many of the topics are extraordinarly well presented, as for example, the treatment of the Maxwellian distribution of velocities in a gas. The publishers have done a remarkably fine job of presenting this material, using clear, large-sized type. The one hundred and thirty line drawings, though small, are very clearly lettered for easy interpretation.

The author has stated that "after careful consideration" a deliberate policy was followed in the order of presentation of the material. Such a policy was responsible for the omission of a chapter on temperature measurement. In consequence of this, as an illustration, the student deals with thermocouples during the first three hundred and twenty pages of the book before he learns, in chapter nine, under the heading of thermal conduction, just what a thermocouple is.

It is, of course, the prerogative of an author to treat the material in whatever manner he deems desirable. It is equally the responsibility of the reviewer to comment upon any marked digressions from what might be expected. A few instances of this sort will be mentioned. The mechanical equivalent of heat, usually allowed a chapter, is treated here completely in little more than one page. The very important subject of specific heat theory is presented briefly in about five pages, mentioning only the theory of Debye. No explicit definition of temperature is attempted as is usually expected at the beginning of a philosophically sound course in heat.

At the end of each chapter is a group of numerical problems which range from those of quite elementary caliber to others that are sufficiently difficult to tax the

ingenuity of any student. The solution of these problems by the student should be valuable training.

A list of references for supplementary reading is appended at the end of each chapter. It is noteworthy that amongst all the references given not once is any mention made of any one of the large number of excellent contemporary texts on heat and thermodynamics. Such neglect on the part of the author occasions some surprise.

J. M. Cork
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Radio at Ultra-High Frequencies, Vol. II (1940–1947). Members of RCA Staff. Price $2.50.

The *RCA Review*, which is the technical journal of the Radio Corporation of America, is well known among research workers in all fields of electronics and communications. It includes detailed reports by RCA engineers of the progress on the numerous problems on which they are working. Some of these papers are reprinted from other technical journals, although the *RCA Review* may remain the principal source of much information.

Owing to the varied nature of the papers that are contained in the *RCA Review*, the publishers have found it expedient to collect the papers that have appeared relating to some given field, and to publish them in bound form. Radio at Ultra High Frequencies, vol. II, is the eighth volume in the RCA Technical Book Series, and the second on the general subject of radio at the higher frequencies. The present volume covers the period from 1940 to 1947, vol. I having covered the period from 1930 to 1939.

The present volume is divided into seven sections: antennas and transmission lines; propagation; reception; radio relays; microwaves; measurements and components; and navigational aids. It also includes in the appendix the summaries of all papers that appear in vol. I, which is now out of print. In addition, the appendix includes a bibliography of technical papers by RCA authors in the period 1925–1947. All of the papers are presented in a high technical degree of competence, which is undoubtedly the policy of the editors.

The volume can serve no purpose beyond that of the original *RCA Review*, *viz.*, as a record of the technical activities of the RCA staff. However, it does so in a convenient way, since the articles have been compiled in convenient form. For this reason alone, it is a volume that would be most useful to any person who is interested in these particular fields of research.

A feature of this particular volume is that it contains several articles which have since become recognized as basic source material in the field. A number of the articles on signal-to-noise analysis, and the relation of the signal-to-noise ratio to the noise factor of a receiver are particularly important.

This is not a book with textbook qualities, and would therefore have a relatively limited appeal to the student or one with general interests. It is the sort of volume that every research worker in the uhf field should have on hand, and to which he will frequently refer.

Samuel Seely
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New Members of the Association

The following persons have been made members or junior members (J) of the American Association of Physics Teachers since the publication of the preceding list [*Am. J. Physics* **17**, 50 (1949)].

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